SPATIAL STRUCTURE OF GAS DYNAMIC CHARACTERISTICS IN A GLOW DISCHARGE WITH A SUPersonic AXISymmetric GAS FLOW

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Abstract. The paper presents the results of theoretical calculations of the gas-dynamic parameters of a supersonic flow in an axisymmetric Laval nozzle for the case when the central body removed from the nozzle serves as one of the glow discharge electrodes. It is shown that the presence of a supersonic flow makes it possible to establish a stationary inhomogeneous density of gas particles between the cathode and the anode of a glow discharge. The density of gas particles near the cathode and anode may differ by tens of times. The results of the study of the glow pattern of a discharge with a supersonic gas flow are presented. The dependence of the characteristics of the glow discharge on the distribution of inhomogeneous gas density in the interelectrode region is revealed. This effect opens up new possibilities for the use of discharges with supersonic gas flow for nanocoating and synthesis of nanostructures.

1. Introduction
To date, the glow discharge is widely used in gas discharge tubes as a light source, when applying protective, decorative, functional coatings, in lasers, textile, construction, military industries, medicine and other spheres of human activity. Each new application of the glow discharge is associated with new specific features. For use as a light source, it is a high efficiency and a long service life, in lasers it is high power, in medicine it is low voltage. When applying functional surfaces, a strong vacuum of the working gas in the gas discharge chamber is required. At the same time, it is necessary to provide a condition when the atom knocked out of the cathode reaches the substrate without experiencing a single collision. On the other hand, there should be a sufficient number of ionizing collisions of electrons in the cathode region. Usually this problem is solved by applying the magnetron effect, when the Lorentz force acting on the electron keeps it in the cathode region, increasing the probability of ionizing collisions of electrons in this region.

However, there are other ways to solve this problem. One of these is the organization of supersonic gas pumping in the glow discharge area. Gas-dynamic aspects of the interaction of a transverse glow discharge with a supersonic flow in a heat source model based on the Navier-Stokes equations were numerically studied in [1]. Axisymmetric flows are calculated for a uniform oncoming flow. In [2–5], studies of a glow discharge in miniature flows at atmospheric pressure were carried out. Nozzles with a diameter of about 100 μm serve as electrodes in such discharges. Such discharges are called plasma microjets. In [2], a method was proposed for creating microplasma in the atmosphere by controlling a glow discharge with a gas flow emanating from a nozzle. Such an organization of the discharge makes
it possible to effectively use the entire volume of the glow discharge plasma for surface treatment. The authors of [3] studied the glow discharge plasma formed as a result of the intersection of two flows of glow discharge plasma in helium. The authors of [4] carried out two-dimensional numerical simulation of such discharges. The characteristics of an atmospheric glow discharge plasma in a complex gas flow consisting of helium surrounded by a flow of nitrogen or a mixture of nitrogen and oxygen were studied in [5]. The external flow in this case shielded the discharge plasma from the atmosphere. The method of influencing the characteristics of a glow discharge using a supersonic flow was also investigated and developed in [6–9].

The organization of supersonic gas pumping made it possible to form regions with different concentrations of neutral particles in the gas discharge chamber, which in turn led to a different spatial distribution of the electrophysical characteristics of the glow discharge.

In the same work, the study of a glow discharge in a supersonic gas flow has been further developed. The main difficulty in organizing the interaction of a glow discharge with a supersonic gas flow is that the discharge tends to bend around the supersonic jet. In contrast to the previously considered methods of organizing gas pumping, in this paper it is proposed to immerse one of the electrodes in a supersonic flow so that it is completely surrounded by it. And the other electrode should be made in the form of a ring around the first one. At the same time, the supersonic gas flow will create an inhomogeneous density on the gap of the glow discharge from the cathode to the anode without the possibility of bending the gas flow by the discharge.

2. Theoretical representation

Before conducting an experiment to study the effect of supersonic gas flow on the spatial distribution of glow discharge zones, a numerical simulation of gas flow through a Laval nozzle with a central body was carried out in the Ansys software package. The simulation allowed us to obtain a theoretical representation of the glow pattern, as well as the distribution of gas density, gas flow velocity and temperature, as well as the Mach number in the discharge chamber.

An ideal gas model was used in the calculations. The system of Navier-Stokes equations was solved together with the energy balance equation. The parameters of the Laval nozzle with a central body were taken as parameters of the nozzle, which was supposed to be used in experiments.

Figure 1 shows the results of calculations of gas flow velocity distributions (Figure 1a) and Mach numbers (Figure 1b) in an infinite axisymmetric space at an inlet pressure of 760 Torr and an initial outlet pressure of 10 Torr. In the core of the supersonic flow, the outflow velocity reaches up to 2 M. The boundaries of the supersonic gas flow are also clearly visible. There is a border region near the central body where there is no supersonic flow.

![Figure 1](attachment:image1.png)

**Figure 1.** Results of simulation of gas flow outflow in the Ansys program.

Figure 2 shows graphs of the dependence of the gas flow rate and temperature on the distance from the surface of the cylindrical central body in the plane passing through the anode plane at a distance of 10 mm from the nozzle outlet section. The surface of the cylindrical central cathode body corresponds to the coordinate of 1.5 mm.
Figure 2. Distribution of gas flow velocity and temperature in the radial direction in the plane of the electrodes.

A boundary condition of adhesion was set on the cathode surface, so the flow velocity near the cathode surface drops to zero. The sound velocity is achieved at a distance from the cathode equal to ~ 0.25 mm. The core of the supersonic flow falls at distances from 1 mm to 6 mm from the cathode surface. The flow velocity in this area reaches values of more than Mach 2.

Figure 3 shows the distributions of particle concentration and gas pressure in the same section.

According to the calculations carried out in the Ansys program, it can be seen that the gas flow formed by the Laval nozzle makes it possible to create an inhomogeneous distribution of gas particles in the interelectrode space. In particular, the concentration of particles in the core of the gas stream is about fifty times greater than in the rest of the flow. Such a distribution of particle concentration should lead to compression of the cathode regions. In this regard, it is easier to place the ring electrode in a sparser area of the discharge chamber. If there is a cathode in the rarefied zone, then all the near-electrode regions will have to shift to a zone with a supersonic gas flow near the anode.

3. Experimental setup

The experimental setup (Figure 4) included a vacuum system, a gas supply system, an electric power supply system, as well as measuring instruments and a gas discharge chamber.

![Experimental setup diagram](image)

Figure 4. Experimental setup diagram.

The gas discharge chamber is a vacuum dome, into which hoses for pumping and supplying air are connected, as well as two electrical wires for connecting the cathode and anode. Under the dome, the Laval nozzle with a central body is axisymmetrically arranged, which serves as one of the electrodes around which the second ring electrode is located, and the confuser (Figure 5).
Figure 5. Discharge device with supersonic gas flow. 1 - supersonic nozzle with a central body; 2 - ring electrode-the second electrode; 3 – confuser; 4 - The central body is the first electrode; 5 - Attachment of the nozzle - confuser system.

The diameter of the nozzle in the critical section $d_1 = 3.5$ mm, and in the output section $D_1 = 8$ mm, the diameter of the cylindrical central body throughout is $d_2 = 3$ mm, the area of the critical section $S_1 = 2.6$ mm$^2$, the area of the output section $S_2 = 50.3$ mm$^2$. The length of the nozzle diffuser is $l_1 = 12$ mm, while the central body protrudes beyond the nozzle at a distance of $l_2 = 30$ mm. At a distance of $l_3 = 10$ mm from the outlet section of the nozzle, an annular electrode with a diameter of $d_3 = 14$ mm is located axisymmetrically to the central body.

4. Experiment

First, a discharge was ignited in the chamber, while in the absence of a gas flow, near-electrode zones were observed, as well as a Faraday dark space (Figure 6a, the central body is the cathode). Further, when the gas flow was supplied and a supersonic flow was formed, the near-electrode regions were pressed against the central body (cathode). Along with this, there was an increase in the Faraday dark space, and the positive table was practically absent (Figure 6b).

Figure 6. The picture of the discharge glow. $U=500$ V, $I=50$ mA

Such a glow is possible provided that a region with a high content of particles injected by a Laval nozzle with a supersonic gas flow is formed near the cathode. On the slice passing through both electrodes, the area with an increased concentration of gas particles occupies about 3 mm. At the same
time, the region with supersonic flow velocity extends up to 7 mm from the surface from the central
electrode. As a result of the experiment, it was found that the experimental studies are in good agreement
with the results of the calculation of the glow discharge and with the discharge glow patterns for the
case when the central body is a cathode.

5. Conclusions
Theoretical and experimental studies of the possibility of controlling the structure and parameters of a
glow discharge in a supersonic gas flow between the central body of the nozzle and an annular electrode
around the central body are carried out. This experiment differs from previous studies in that such a
relative position of the electrodes in relation to each other excludes the possibility of the discharge of
the gas flow. Due to supersonic gas pumping through the glow discharge region, it was possible to
narrow the near-electrode discharge regions. As the discharge current increases, the positive column
increases outside the region with supersonic gas pumping. Such a way of organizing the discharge can
be used in the processes of applying functional coatings.

Low-temperature plasma can be used for the synthesis of various nanostructures and is well suited
for the modification of various surfaces. This is shown in many works [10-12].

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