The Influence of Supersonic Gas Stream on Spatial Structure of Glow Discharge

B A Timerkaev¹ and R S Shamsutdinov¹

¹A. N. Tupolev Kazan National Research Technical University

Abstract. This work investigates into the properties of longitudinal glowing discharge in supersonic gas stream between central body and reducer. It has been established that the properties of discharge spatial localization, intensity of radiation, formation of near-electrode areas directly depend on arrangement of supersonic stream. This work analyzes the properties of gas stream in expanding area of supersonic nozzle, pressure recovery in reducer. It has been experimentally established that gas circulation at supersonic speed in the area of glowing discharge makes it possible to control the distribution of concentration of neutral particles in interelectrode space as well as localization of near-electrode zones and positive glow.

The glowing discharge in supersonic gas flow in micronozzles with central body was initially studied in [1-3]. In these works, the discharge was arranged in traversal direction with regard to supersonic stream. Supersonic nozzle with central body was used both for formation of supersonic jet and acted as electrodes of glowing discharge. Such geometry of electrodes allowed to provide numerous possibilities to arrange glowing discharge in supersonic stream aiming at increase in specific energy contributions to discharge while retaining high degree of non-equilibrium between electron temperature and gas temperature. In addition, the discharge stability was also increased significantly.

Discharges in transversal supersonic gas stream are studied in [4-5] with regard to decrease in aircraft drag and inflammation of air–fuel mixture in supersonic streams. Dynamics of propagation of pulse transversal discharge in supersonic jets was studied in [4] by rapid photographic recording. It has been demonstrated that the stream does not destroy the discharge channel but drifts it, determining the propagation rate and, respectively, configuration of the discharge channel. Since the transversal discharge always contains a part of channel perpendicular to the stream, such discharge cannot be stationary in principle. The discharge extension along the stream is restricted by repeated breakdowns related with one of two mechanisms of instability. The first mechanism is stipulated by instability caused by external electrical circuit, herewith, the repeated breakdown is a consequence and not the cause of oscillating pattern of discharge glow.

Microscopic parameters of plasma of pulse and stationary transversal discharges in supersonic air jet exiting into flooded space were studied in [5] by spectrometry and probe method. The measurements were performed for the Mach number M = 2, the pressures of flooded space p = 30–200 Torr, and the discharge currents I = 1–10 A. Average gas temperatures, concentration of charged particles, and reduced electric field were measured as a function of discharge current.

Recently there has appeared a new trend of studies of glowing discharge in miniature streams at ambient pressure [6-8]. Nozzles with the diameter of about 100 µm are used as electrodes. Such discharges are referred to as plasma microjets, they allow to create plasma of glowing discharge with low currents and voltages of about several kilovolts at ambient pressure. A method of generation of microplasma by controlling glowing discharge by gas stream exiting from nozzle was proposed in [6].
The discharge chamber was comprised of anode, which was the nozzle with the internal diameter of 200 μm, and cathode made of metal mesh with the cell sizes of 54×54 μm. The interelectrode distance was varied in the range from 100 to 1,000 μm. The gas flow rate was 1.7 l/s, the voltage between the electrodes was 1,500 V. An advantage of such discharge arrangement is possibility to efficiently use all bulk of plasma of glowing discharge for surface treatment.

The researchers in [7] analyzed plasma of glowing discharge generated by crossing of two streams of glowing discharge plasma in helium with the diameter of 0.5 mm under various angles. The discharge distance between the electrodes along the lines of current was 7 mm. In the experiments, the discharge current was 10 mA, the discharge voltage was 1,600 V, the gas flow rate through each nozzle was 7 l/s. The researchers in [8] carried out 2D numerical simulation of such discharges. Helium was used as working gas and nitrogen was used as reference gas. The simulation gave the region with increased mole portion of helium near the axis with radius of about 0.25 mm: this was attributed to the fact that helium atoms had no sufficient energy to force nitrogen atoms and to occupy large region in the stream due to lower weight.

This trend was further developed in [9-12]. These works analyzed discharge between flat electrodes; and supersonic stream was arranged in restricted region of interelectrode gap. Herewith, the directions of intensity of electric field and supersonic stream were mutually perpendicular. It was demonstrated that in this region of interelectrode gap, the concentration of gas particles differed from that in other regions. This effect allowed to control generation of near-electrode areas of glowing discharge and to estimate possibilities to use such discharges upon application of functional coatings. This work continuing the studies in [9-12] analyzes the discharge in supersonic gas stream, which is longitudinal to direction of electric field.

As the preliminary studies have demonstrated, when the electrodes are installed beyond the supersonic jet, the discharge tends to bypass the supersonic stream. If the electrodes are submerged into the supersonic jet, then the supersonic stream is disturbed causing shock waves leading to deceleration of the supersonic jet. Therefore, the most optimum solution to arrangement of the discharge in longitudinal supersonic gas stream should be based on the use of central body and metal reducer as electrodes. In this case, the lines of intensity of electric field cross the lines of gas stream but only in longitudinal direction.

The laboratory rig for studying discharge in supersonic gas stream is comprised of the variable power source, the vacuum pump, gas ballast receiver combined with discharge chamber of gas dynamic unit, instruments and controls (Fig. 1).

The discharge chamber (Fig. 2) is a hollow cylinder made of molybdenum glass with the length \( l = 80 \) mm and the internal diameter \( d = 20 \) mm. It contains axisymmetric shaped nozzle with central body and metal reducer.
The axisymmetric shaped nozzle with the central body is required for arrangement of supersonic stream. The end sides of the discharge chamber are equipped with clamps for diffusor, reducer, and central body. The gas supply system allows to vary gas flow rate to the discharge chamber, hence, to adjust pressure inside the chamber and behavior of glowing discharge in supersonic longitudinal gas stream.

The cylinder bases contain the reducer and de Laval nozzle with central body. The reducer is made of metal and used as an electrode (anode). De Laval nozzle is an axisymmetric shaped nozzle with central body. The central body is also made of copper and coated with nickel. The central body in the experiments also acts as an electrode (cathode).

The pressure in the chamber and in the receiver was measured by a Testo 520 digital vacuum meter as well as U-shaped mercury manometer. The potential difference on electrodes was obtained by high voltage power source equipped with ammeter and voltmeter. Air was pumped off by means of a rotary vane vacuum pump, Series 2X.

Initially glowing discharge in discharge chamber was obtained in stationary gas at the pressure of about 2 Torr (Fig. 3a). Then, gas was supplied by the pump through rotameter. The gas flow rate was in the range of 9–10 mg/s. At such flow rates the pressure in discharge region was about 20 Torr. Figure 3b illustrates the discharge flow in supersonic gas stream. Occurrence of glowing jet of supersonic gas stream in the region of glowing discharge can be observed visually.

![Figure 3a](image1.png) *Glowing discharge in stationary gas. Air pressure: 20 Torr. Position of electrodes as in Fig. 2.*

![Figure 3b](image2.png) *Glowing discharge in longitudinal supersonic gas stream, Pressure: 20 Torr.*

![Figure 3c](image3.png) *Discharge glow: U= 1800 V, I= 25 mA, p = 22 Torr. Negative glow is observed. Faraday dark space. Positive column has not been formed. Negative glow is restricted by the stream and follows along the stream lines.*

![Figure 3d](image4.png) *Discharge glow: U= 1800 V, I= 40 mA, p = 22 Torr. Positive column in the form of hollow cylinder has been formed. Thin layer of Faraday dark space appeared between negative glow and positive column.*
It was established that the current voltage characteristic of discharge in longitudinal supersonic gas stream was strictly horizontal. The voltage on discharge depends on several factors, the main of which are interelectrode distance, gas flow rate and pressure in the discharge region, gas type, and material of electrode. Herewith, the distribution of current density along cathode for central body was heterogeneous and was determined as follows:

\[ I(x) = \int_{0}^{x} j[p(x)]ds(x), \]

where \( j[p(x)] \) was the current density on cathode as a function of pressure distribution along cathode. With the increase in pressure upstream, the current rapidly increases. The pressure distribution along the central body was determined by reference values of gas dynamics functions. The distribution of current density along cathode for central body at various pressures at input is illustrated in Fig. 4.

![Figure 4. Distribution of current along cathode for three pressures at input. Squares in the plot denote the pressure of 2.6 \( \times \) 10^5 Pa, circles: 1.8 \( \times \) 10^5 Pa, triangles: 1.1 \( \times \) 10^5 Pa.](image)

Therefore, it has been experimentally established that application of longitudinal supersonic gas stream in the region of glowing discharge allows to control the concentration of neutral particles in central part both of the chamber itself and the discharge. It its turn this process promotes formation of regions with various intensities of electric field \( E \) in various areas of the chamber.

The intensity of electric field is maximum in the vicinity of central body of the nozzle, herewith, the concentration of neutral particles \( n \) in this place is minimum. Therefore, the reduced intensity of electric field \( E/n \) in this area is also minimum. With the increase in the distance to the central body, the concentration of neutral particles \( n \) increases together with the decrease in the intensity of electrical field \( E \), which in its turn leads to rapid decrease in the reduced intensity \( E/n \). Herewith, negative glow formed by supersonic stream can be visually observed.

References

[1] Dautov G Yu and Timerkaev B A 1996 Generatory neravnoykh gazorazryadnoi plazmy. [Generators of non-equilibrium gas discharge plasma] (Kazan: Fan)

[2] Galeev I G, Goncharov V E, Timerkaev B A, Toropov V G and Faskhutdinov A K 1990 High Temperature 28(5) 623-6

[3] Galeev I G, Goncharov V E, Timerkaev B A, Toropov V G and Fahkhrutdinov I K 1992 High Temperature 30(3) 342-6
[4] Ershov A P, Surkont O S, Timofeev I B, Shishkov V M and Chernikov V A 2004 *Teplofizika vysokikh temperatur* 42(4) 516

[5] Ershov A P, Kalinin A V, Surkont O S, Timofeev I B, Shibkov V M and Chernikov V A 2004 *Teplofizika vysokikh temperatur* 42(6) 856-64

[6] Yokoyama T, Hamada Sh, Ibuka Sh, Yasuoka K and Ishii Sh 2005 *Journal of Physics D: Applied Physics* 38 1684

[7] Shirai N, Ibuka Sh, Ishii Sh 2008 *IEEE Transactions on Plasma Science* 36(4) 960

[8] Tochikubo F, Shirai N and Uchida S 2011 *Applied Physics Express* 4(5) 056001

[9] Timerkaev B A and Zalyaliev B R 2014 *High Temperature* 52(4) 471-4

[10] Timerkaev B A, Zalyaliev B R, Karimov B R and Israfilov D I 2013 *Vestnik KGTU* 4 198-291

[11] Timerkaev B A, Zalyaliev B R and Saifutdinov A I 2014 *Journal of Physics: Conference Series* 567(1) 012032

[12] Saifutdinov A I, Timerkaev B A and Zalyaliev B R 2014 *Journal of Physics: Conference Series* 567(1) 012031