Experimental study of pulsed gas discharge dynamics in a solenoidal magnetic field

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Abstract

An electric discharge is implemented in a gas at the end of a non-conducting cylinder between the central electrode coaxial with the cylinder and the ring electrode located on the cylinder surface near the cylinder end. The cylinder axis coincides with the axis of a magnetic coil winded on the lateral cylinder surface. The shape of the gas discharge and distribution of thermal emission centers on the surface of the ring electrode when varying the discharge current and the magnetic induction are investigated. In addition, the dynamics of the gas discharge in a solenoidal magnetic field at the outlet of a supersonic conical nozzle is also investigated. In this case, the discharge is ignited between the nozzle sidewall and a rod located along the nozzle axis.

1 Introduction

Within the cycle of the works conducted at the Ioffe Institute when tackling the problem of magnetohydrodynamic control of a supersonic flow as an object under study we employed a model with an electromagnetic facility in a supersonic nitrogen flow. This model is a sharp 60° cone mated with a cylinder of 34 mm in diameter at the surface of which a solenoid is located. One of the ends of the solenoid is connected with a metal ring electrode located at the model surface at the place of conjugation of the cone with the cylinder. The other solenoid end is connected to one of the terminals of an external pulsed voltage source. The other source terminal is connected with the central electrode shaping the cone vertex.

In the gap between the central and ring electrodes an electric discharge is ignited which is sustained by the external voltage source. Thus, the gas discharge was implemented in the solenoidal magnetic field near the conical surface of the model. In work [1] an appreciable dependence of the dynamics of such a discharge on the polarity of connection of the electromagnetic facility to the voltage source was detected, in particular, when changing the connection polarity the frequency of rotation of the discharge changed by two times.

To elucidate the reasons for such a dependence an experimental setup was designed and constructed and additional investigations were conducted [2] that showed that the discharge motion is governed by the dynamics of the cathode spot over the surface of the ring electrode and by action of the ponderomotive force. Interference between these two physical processes may lead to various effects, for example, to redistribution of the heat load over the model surface, which is noted by the authors of [2].

The present work is devoted to the further study of possibilities of employment of magnetohydrodynamic effects in gasdynamic experiments, in particular, to investigation into dynamics of the gas discharge in the soleniadal magnetic field under the conditions when an appreciable influence is exerted by physical processes at the electrode surface. First of all we keep in mind so-called anomalous motion of the cathode spot which consists in capability of the cathode spot to move in a solenoidal magnetic field in the direction opposite to the action of the ponderomotive force [3, 4, 5].

2 Experimental setup

Figure 1 shows schematic of the experimental setup consisting of vacuum chamber 1, electronic recorder 2 of images in the visual range, and pulsed voltage source 3. The vacuum chamber has the cylindrical shape of 0.3 m in diameter and 0.4 m in height. The setup is equipped with a vacuum pump for evacuation of air and with the system for control of the pressure.

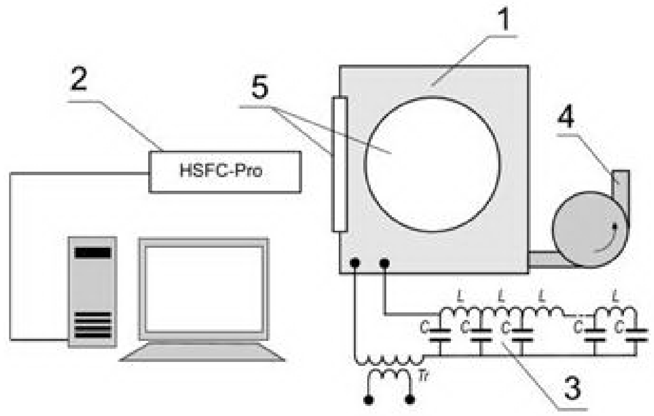

Figure 1: Experimental setup

At the lateral surface of the chamber windows 5 are located for optical recording of the process under study. As the recorder of the images 3-channel digital camera HSFC-Pro is used which enables one to take up to 6 images of 1280x1280 pixels in sizes in a single experiment with the exposure time 10^{-6} s. Electronic images taken by the camera are transmitted into a computer for the subsequent processing of them and analysis.

The pulsed voltage source is an LC lumped-constant line charged before the experiment up to the desired voltage. High-voltage transformer Tr of small inductance is connected in series into the discharge circuit. To the primary winding of the transformer a short pulse of the duration about 10^{-6} s is applied. The secondary winding of the transformer forms a pulse with the amplitude up to 30 kV which initiates operation of the electromagnetic facility. The voltage source is connected with the electromagnetic facility via hermetic connectors.

One of the models employed in the experiments the schematic of which is shown in Fig. 2 is made from a dielectric material in the shape of cylinder 1 of 100 mm in diameter. The electromagnetic facility consists of magnetic coil 2 containing 16 winds of a cupper wire of 1 mm in diameter and two electrodes. In the center of the end of the dielectric cylindrical barrel central electrode 3 is located, second electrode 4 in the shape of the open ring is located on the cylindrical surface of the barrel near the magnetic coil. One of the end of the coil is connected with the ring electrode. The other coil end and the central electrode are connected with the terminals of the voltage source.

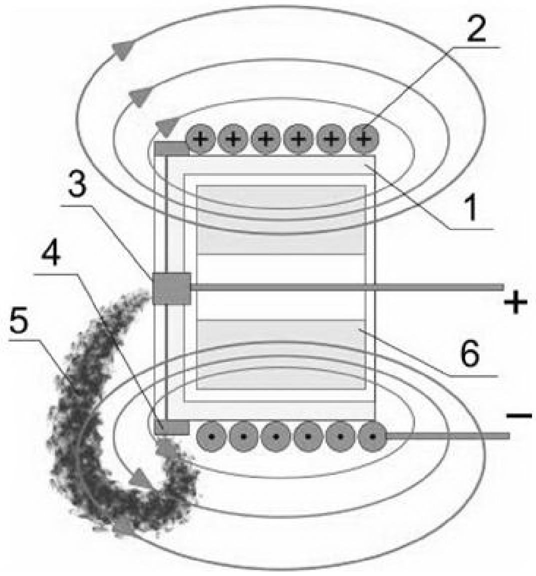

Figure 2: Electromagnetic facility located at the end of the dielectric barrel.

The triggering high-voltage pulse causes electric breakdown 5 between the central and ring electrodes outside of the cylinder and close the discharge circuit of the external voltage source involving the magnetic coil and air gap placed in series. The discharge of the voltage source occurs during about 10^{-3} s, the current strength attains about 10^3 A. In the magnetic field of the coil the gas discharge gains rotational motion around the model axis under the action of the ponderomotive force.

The model structure allows one to position inside the barrel magnetic core 6 which is a steel tape of 25 mm in width and 0.2 mm in thickness curled into a spiral and spaced between the winds with an insulating tape. As the measurements showed the core increases the magnetic induction on the average by 40 - 50 % at other conditions being equal.The electromagnetic facility described above was also employed with another model whose schematic is shown in Fig. 3.

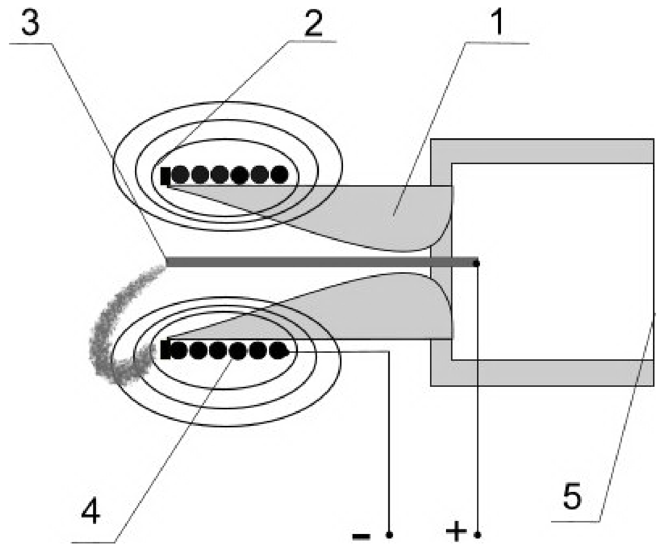

Figure 3: Supersonic nozzle with the electromagnetic facility.

The model is supersonic conical nozzle 1 with the opening angle 60° with the critical and outlet cross sections 10 mm and 60 mm, respectively. At the cone sidewall ring electrode 2 is located and along the cone axis there is metal rod 3 of 4 mm in diameter playing the role of the central electrode. On the outer surface of the nozzle solenoid 4 is located. One of the solenoid ends is connected with the ring electrode. The other solenoid end and the central electrode are connected with the terminals of the voltage source.

The supersonic section of the conical nozzle is located inside the vacuum chamber within the view field of the optical device, and the subsonic section is separated from the atmosphere by a plastic diaphragm. Before the experiment the chamber is pumped out and at the moment of breakdown of the diaphragm air starts to flow into the chamber via the nozzle. According the results of a one-dimensional stationary calculation the air pressure at the nozzle outlet is comparable with the residual pressure in the vacuum chamber which in the course of time may lead to emergence of flow separation inside the nozzle [6]. The calculation shows that during approximately 1 ms after the beginning of the process the pressure does not exceed the pressure at the nozzle outlet cross section larger than by two times. At such a ratio of the pressures flow separation inside the nozzle is an unlikely event. Within this time interval the gas discharge occurs and recording of the image is implemented.

3 Discharge near the cylinder end

The subject of research is the shape and structure of glow of the gas discharge and also behavior of the thermal emission centers on the ring electrode. These data are obtained from the analysis of the electronic images corresponding to radiation in the visual spectrum range at the constant air pressure inside the test chamber equal 2 kPa.

In the following we shall characterize discharge current I by its average value during the pulse duration, and as a scale of magnetic induction B we adopt its value at the center of a wind of 100 mm in diameter with the current flowing through it equal the product of average current I by the number of the coil winds equal 16 in the given case. The experiments were carried out at two values of the initial voltage of the voltage source. In accordance with this, we shall characterize the regimes of operation of the electromagnetic facility by the following parameters: regime 1 - average discharge current I = 1 kA, average magnetic induction B = 0.2 T; regime 2 - average current I = 1.7 kA, magnetic induction B = 0.3 T.

The typical shapes of the pulses of the discharge current and magnetic induction are shown in Fig. 4. The induction is calculated with the use of the signal of a magnetic coil of 4 mm in diameter which was located at the barrel end normally to the barrel surface.

Similar to work [1] here it is experimentally affirmed that the variant of connection of the ring electrode with the negative terminal of the external voltage source is promising from the point of view of influence on the gas discharge structure.

All the following results are obtain just at such connection of the external voltage source, and term "cathode spot" refers to the thermal emission center on the ring electrode.

Figure 5 demonstrates images of gas discharge glow taken from the side of the model end at various time instants from the process beginning (a - 0.3 ms, b - 0.4 ms, c - 0.5 ms, d - 0.6 ms) and corresponding to different regimes of operation of the electromagnetic facility (regime 1 - upper row, regime 2 - lower row).

At the centers of each of the frames the dark spots on the bright background mark the image of the center electrode of 6 mm in diameter which is the anode (it connected to the positive terminal of the voltage source). The bright spot of the practically circular

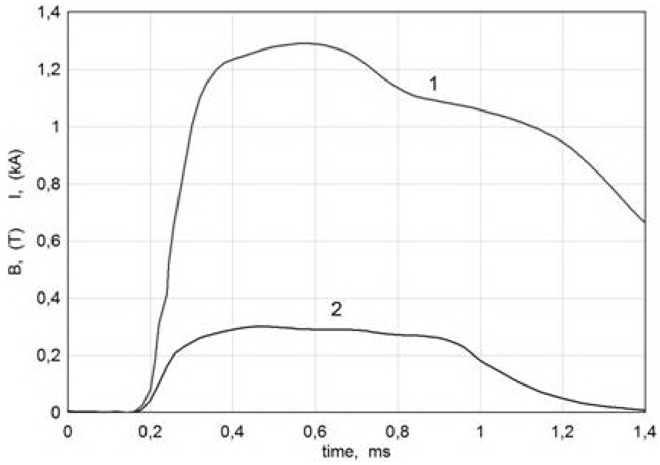

Figure 4: Typical shapes of pulses of the discharge current (1) and magnetic induction (2).

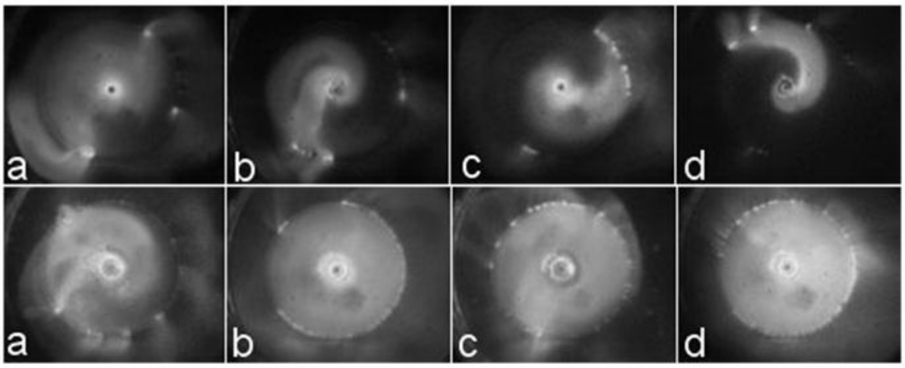

Figure 5: Glow of the gas discharge at various time instant from the process beginning (0.3 ms, b - 0.4 ms, c - 0.5 ms, d - 0.6 ms).

shape encircling the central electrode corresponds to the intense glow of the discharge in the vicinity of the anode where concentration of the discharge current occurs. According to our estimates obtained on the basis of analysis of the taken images the current density in this region amounts to $10^7 - 10^8$ A/m^2.

To the position of the ring electrode in the photographs there correspond images of bright single points in the upper photographs and the group of points in the lower ones that are located about the center. They are cathode spots (group of spots) that are the centers of thermal emission of electrons from the ring electrode surface.

In the images of the upper row (regime 1) in the gap between the electrodes the single current channel is distinctly seen; the current channel is spirally twisted clockwise by the ponderomotive force. The inner structure of the channel is non-uniform over the transversal cross section - separate channels are observed that close on the brighter cathode spots.

In the course of time the number of the cathode spots changes inconsiderably, and at a certain time instant (Fig. 5-c) isolated spots form a compact group which then takes the view of single centers. Bright spots that are not related with the anode via the current channel are also observed.

Presumably they are decaying "old" cathode spots the current through that either weak or ceases, but the electrode surface cools still not sufficiently and continues to glow.

As it was said above the ponderomotive force is directed clockwise. However, the spiral current channel moves in the opposite direction which is readily detected when the photographs are sequentially inspected.

When the discharge current and magnetic induction increase (regime 2) the pattern appreciably changes. The number of the cathode spots on the ring electrode surface considerably increases. They are placed in groups and their distribution over the circumference becomes more uniform. The space between the electrodes, excepting for regions directly adjoining the electrodes, also takes the uniform light-striking which, probably, is related with more uniform distribution of the current than in the previous case. At that, the glow intensities of the current channel in both cases are practically identical.

Simultaneous variation of both the discharge current and the magnetic induction is attained by varying the initial voltage of the external source. Therefore, to estimate the influence of the magnetic field on the discharge dynamics we compared images taken with the model equipped with the magnetic core and without it at the same average value of the average discharge current. An analysis showed that the magnetic core increasing the magnetic induction on the average by 1.4 time does not cause noticeable changes in the dynamics of the gas discharge and in location of the cathode spots on the ring electrode.

Taking photographs laterally showed that the current channel propagates from the end of the barrel in all directions extending to the distance approximately equal the barrel radius. In the photographs shown here this manifests itself in emergence of bright "tails" on the outer side of the ring electrode that adjoin the cathode spot. The "tails" deviate clockwise by the ponderomotive force directed identically on both sides from the ring electrodes.

Naturally, the barrel end bounds the region of propagation of the discharge. About that how the size of the region of propagation of the discharge one can judge using sequence of the photographs shown in Fig. 6.

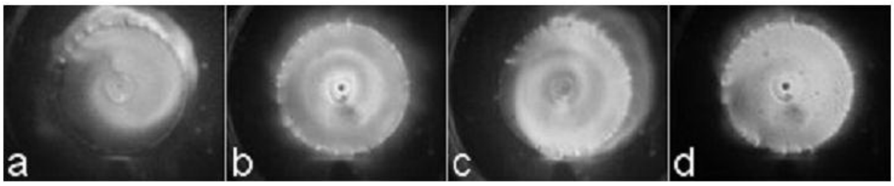

Figure 6: Glow of the gas discharge at various time instants from the process beginning (0.3 ms, b - 0.4 ms, c - 0.5 ms, d - 0.6 ms) when the discharge region was bounded.

The images correspond to operation of the electromagnetic facility in regime 2, however in this case, in parallel with the end of the barrel at the distance 8 mm from it we positioned a glass plate bounding the region of propagation of the gas discharge. An attention is attracted by the noticeably increasing brightness of the glow in the region between the electrodes as compared with the previous cases which evidences higher gas temperature in the discharge region. In the discharge structure emergence of spiral non-uniformities is also observed (compare with the lower row in Fig. 5). Distribution of the cathode spots over the length of the ring electrode becomes more uniform, and the "tail" lengths noticeably decrease.

4 Discharge at the nozzle outlet

Similar to the experiments with the discharge near the barrel end a regime in which the ring electrode is connected to the negative terminal of the voltage source is promising from the point of view of possibilities of control of the process of gas discharge. Figure 7 displays images of the gas discharge corresponding to the negative (Fig. 7.1) and positive (Fig. 7.2) polarity of the ring electrode and at other conditions of the experiment (time instants of the recording, gas pressure, and discharge current) being equal. The bright rings in the images mark position of the ring electrode.

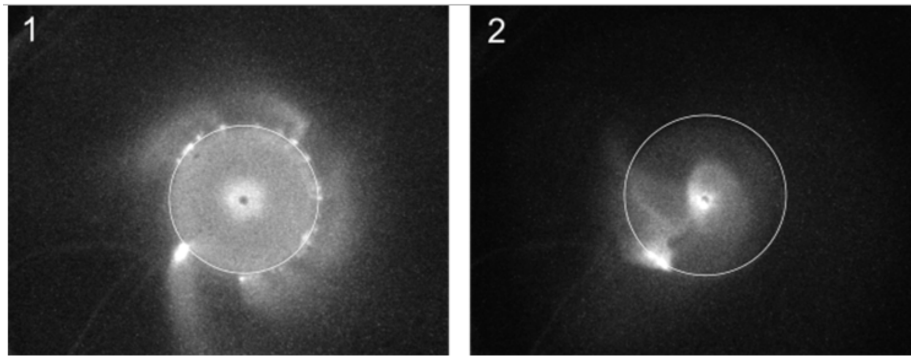

Figure 7: Glow of the gas discharge at the negative (1) and positive (2) polarities of the ring electrode.

Comparison between the images shown evidences appreciable influence of the electrode processes on the discharge dynamics. The further investigations were conducted at the negative polarity of the ring electrode.

Distinction of the discharge in the outlet nozzle cross section from the discharge near the barrel end consists in the absence of a solid surface (glass plate) bounding the region of propagation of the discharge. As it was shown above, this influence may be appreciable. Therefore, for comparison with the previous experiments the first series of experiments with the nozzle was carried out in a quiescent gas at approximately the similar external conditions.

Figure 8 shows images of the gas discharge at the residual gas pressure in the vacuum chamber 100 Pa corresponding to various discharge currents.

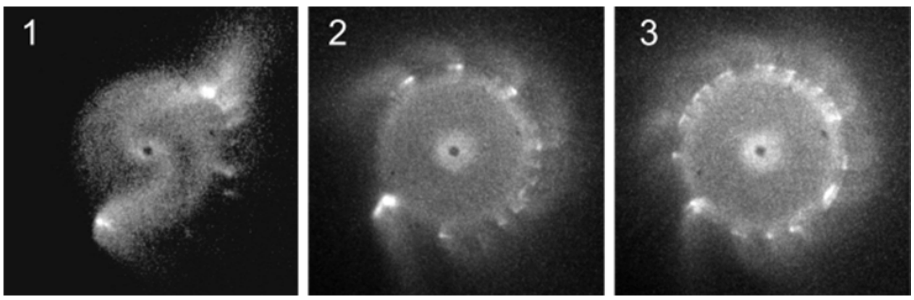

Figure 8: Discharge in a quiescent gas at various discharge currents (view from the side of the nozzle outlet).

An analysis of the sequence of images showed that the dynamics of the gas discharge near the nozzle outlet qualitatively corresponds to the discharge behavior near the barrel end. When decreasing the pressure of the ambient gas, more uniform distribution of the discharge glow is observed in the region of interaction, and when increasing the discharge current the number of cathode spots on the ring electrode increases. In distinction from the previous series of the experiments distribution of the cathode spots on the ring electrode surface is more uniform - the spots are located symmetrically relative to the nozzle axis. The discharge glow in the space between the electrodes (see Figs. 8.2 and 8.3) is uniform enough which enables us to make a supposition about uniform distribution of current in the azimuthal direction.

The presence of the supersonic flow appreciably changes distribution of the cathode spots on the surface of the ring electrode. Figure 9 shows the discharge images taken from the lateral side (Fig. 9.1) and from the side of the outlet nozzle cross section (Fig. 9.2).

In the Fig. 9.1 the white ellipse corresponds to the position of the ring electrode. It is seen that the current channel (bright region in the image) is drawn out in the direction of propagation of the supersonic jet and occupies only a part of the jet.

The circumference of white color in the Fig. 9.2 marks position of the ring electrode. In this case one or two groups of the cathode spots are observed that are distributed non-symmetrically relative to the axis. At that, the discharge "tails" outside of the circumference propagate appreciably farther from the nozzle sidewall in distinction from the discharge in an immovable gas. The space between the electrodes has the uniform light-striking in spite of asymmetry of disposition of the cathode spots on the ring electrode.

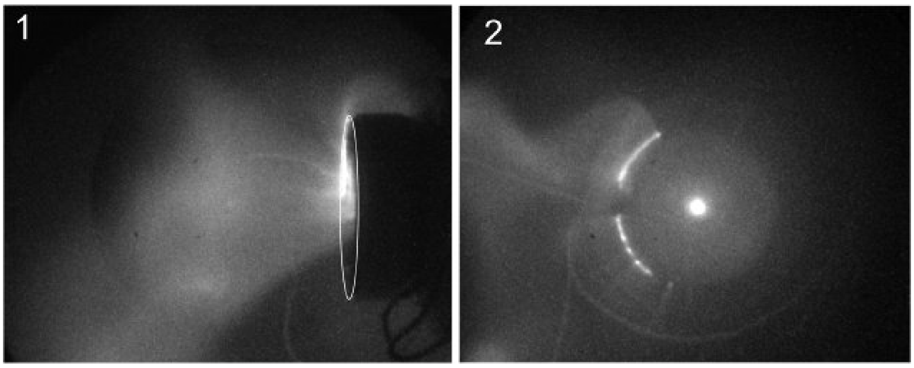

Figure 9: Discharge in the supersonic air flow with Mach number M = 5.5 (1 - view from the lateral side, 2 - view from the side of the nozzle outlet).

5 Conclusion

Similar to investigations [1, 2] carried out earlier, in the investigations into the discharge near the barrel end with the characteristic size larger by three times it was detected considerable influence of the near-electrode processes on the behavior of the gas discharge. The supposition stated earlier concerning that the basic physical mechanisms governing the gas charge dynamics in a solenoidal magnetic field are localized in the vicinity of the ring electrode is also affirmed.

In the case when the ring electrode is cathode the structure and behavior of the discharge is governed by interference between two basic processes: by the action of the ponderomotive force and by the cathode spot dynamics. Both processes depend both on the current strength and on the induction of the magnetic field. Increasing the induction due to employment of the magnetic core at other conditions being equal does not noticeably reflect on the discharge structure in distinction from the investigations mentioned above. Simultaneous increase of the discharge current and magnetic induction appreciably influences on the process under study - the current channel has the spiral shape at a weak discharge current and occupies the whole space between the electrodes when the current increases.

In the presence of the supersonic flow the gas discharge shape appreciably changes - distribution of the cathode spot on the ring electrode becomes asymmetrical the current channel stretches in the flow direction.

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