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Investigation and Application of Nanosecond Discharges for Supersonic Flow Structure Visualization

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Abstract

An experimental study was carried out on the spatial distribution of glow in a nanosecond surface sliding discharge and a combined volume discharge in supersonic air flows around a streamlined axisymmetric body in a channel. The flow in the discharge chamber included shock waves generated by the flow around the body and those reflected from the channel walls. Flow visualization was performed by the direct shadowgraphy and by recording the discharge glow with photo cameras and ICCD camera. Supersonic air flows with Mach numbers of 1.36–1.60 were generated behind plane shock waves with Mach numbers of 3.0–4.4 in a in a rectangular shock tube channel. Discharges were initiated under a voltage pulse of 25 kV either along the surface or within the volume, extending up to 100 mm along the flow direction. Spatial emission characteristics of the discharge initiated at various stages of gas-dynamic flow were analyzed. Digital image processing and analysis of the glow captured during discharge development were carried out and compared with shadowgraphy images of the flow field. A correlation was demonstrated between the emission distribution of the sliding surface discharge in supersonic flows and the state of the boundary layer on the channel wall where the discharge develops. Comparison of volume discharge images with shadowgraphy frames enabled the reconstruction of the three-dimensional structure of the supersonic flow, featuring a bow shock in front of the body and the oblique shock waves downstream.

Keywords: supersonic flow, shock wave, surface sliding discharge, nanosecond combined volume discharge, gas-discharge visualization, high-speed shadowgraphy.

Introduction

Methods of gas-dynamic flows visualization using electric discharges are widely used in plasma aerodynamics [1-5]. The discharges of various types allow not only to organize flow control modes, but also to obtain information about the flow structure [3-5]. Traditional visualization methods, such as the direct shadowgraphy method, the schlieren method and the interferometry, have effectiveness in studying supersonic flows in channels where there are sharp changes in the parameters of the gas, including density and refractive index [1, 2, 6].

In recent decades, visualization methods based on recording the glow of various types of gas discharges have been developed [1, 3-6], in addition to classical methods. These methods can be used at low gas pressures, when the local intensity of the gas discharge plasma glow is directly related to the magnitude of the reduced electric field and the gas density [4-7]. The interaction of shock waves with bodies and boundary layers creates a complex flow field (shocks, rarefaction zones, flow separation), which can affect the shape and intensity of the discharge glow. Volume and surface discharges of nanosecond duration, short compared to gas-dynamic times (~ 1 μs), allow visualization of structural elements of high-speed flows, such as shock waves, oblique shocks and other characteristic flow elements even at high flow velocities [4-6]. In combination with classical methods, registration of gas discharge glow can provide additional information about the three-dimensional structure of a supersonic flow.

Nanosecond surface sliding discharge propagating along a dielectric surface attracts attention due to its potential in plasma control of high-speed flows. Sliding discharge forms a quasi-homogeneous plasma distributed over the area of the dielectric [7, 8]. Compared to other types of surface discharges, the sliding discharge creates a significantly wider plasma zone, which makes it suitable for use in gas-dynamic flows [7, 9, 10].

The aim of the work was to study the distribution of the radiation of a pulsed surface sliding discharge and the radiation of a combined volume discharge in supersonic air flows with Mach numbers of 1.36-1.60, flowing around an axisymmetric blunt body. Based on a comparison of the obtained images and the results of shadowgraphy, the possibility of reconstructing the three-dimensional structure of the gas-dynamic flow in the channel was analyzed.

Experimental conditions

Experiments were carried out on a shock tube with a discharge chamber of rectangular cross section 24×48 mm² (y×z) (Fig. 1). Air at an initial pressure of 10–30 Torr was used as the working gas. A flow with a plane shock wave was formed in the shock tube channel, followed by a homogeneous co-current flow after rupture of the diaphragm [6, 7]. Supersonic air flows with Mach numbers of 1.36–1.55 were generated behind the plane shock waves with Mach numbers of 3.0–4.4. The uniform co-current flow behind the shock wave had a duration of 200–500 μs. An axisymmetric body - a cylinder with a spherical blunting, 7.5 mm in diameter and ~200 mm in length - was mounted in the center of the discharge chamber at a zero angle of attack to the oncoming flow. The nose part of the body, 15-25 mm long, was located inside the discharge volume of 100 mm length of along the direction of the flow. Pressure sensors connected to an oscilloscope were used to monitor the shock wave velocity.

The direct shadowgraphy was used to visualize the flow in the discharge chamber between the plane-parallel quartz side walls of the discharge chamber [2, 6]. The optical scheme of the shadowgraphy included the formation of a plane-parallel light beam passing through the studied area near the streamlined body. A high-speed camera recorded shadowgraphy images at a frequency of 150,000 frames per second. A laser with a wavelength of 532 nm was used as a light source. The optical system formed a parallel beam of light ~40 mm wide, which passed through the quartz walls of the discharge chamber to probe the flow field [6].

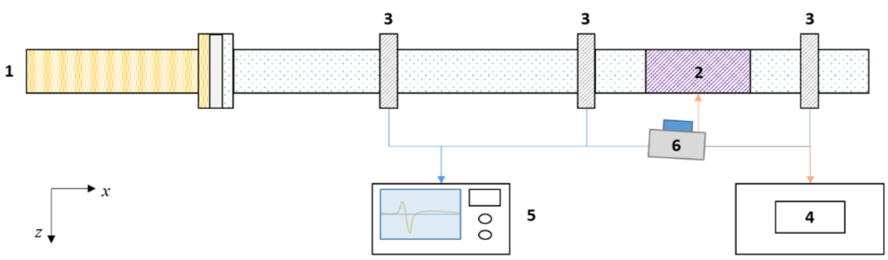


Fig. 1. Experimental setup and diagnostic equipment: 1 — shock tube, 2 — discharge chamber, 3 — piezoelectric pressure sensors, 4 — discharge switch, 5 — oscilloscope, 6 — photo camera/ICCD camera.

A surface sliding discharge with an area of 30×100 mm² (z×x) was initiated on the lower wall of the discharge chamber at a pulse voltage of 25 kV; the discharge current was 1-2 kA [7]. A special electrical circuit was used to form a combined volume discharge. The discharge included two surface sliding discharges on the upper and lower walls of the discharge chamber, located at a distance of 24 mm from each other [11]. When a pulse voltage was applied, the sliding discharges formed the upper and lower plasma electrodes, providing preionization of the volume with ultraviolet radiation. During pulsed discharge, a volume breakdown of the gas occurred, the discharge current reached 1 kA. The duration of the discharge current was ~500 ns.

In the experiments, discharges of two types were realized at different stages of the flow after the shock wave passed the bow of the body until the end of the co-current flow. The discharges initiated by a pulse delay generator relative to the passage of the shock wave through a piezoelectric pressure sensor in the shock tube channel (Fig. 1). Pressure sensors connected to an oscilloscope were used to monitor the shock wave velocity.

The discharge glow was recorded through quartz windows of the discharge chamber at different angles (the exposure time corresponded to the discharge emission time in the visible spectral range); and by ICCD camera with nanosecond resolution. The glow of the surface sliding discharge on the lower wall was recorded at a large angle of inclination to the discharge plane. The discharges emission in air at high electric fields is determined mainly by the bands of the second positive system of molecular nitrogen with a maximum in the ultraviolet range [7, 10, 12]. The photo images were processed using a graphic editor to improve the sharpness and contrast. A comparison of the discharge glow images and the corresponding shadowgraphy patterns of the flow was carried out to reveal a relationship between the discharge plasma emission and the structure of the gas-dynamic flow near the streamlined body in the channel.

Formation of supersonic flow in the discharge chamber

High-speed shadowgraphy showed the formation of a complex system of shock waves during the supersonic flow around the body in the discharge chamber, the areas of boundary layer separation. After the shock wave passes the nose of the blunt body and diffraction occurs, a stationary flow with a bow shock wave is formed. The stationary flow was formed for 30-50 μs during the diffraction and continued for up to 500 μs within the duration of a homogeneous co-current flow under experimental conditions. After the end of the stationary stage, the flow was reconstructed with a change in the shock-wave configuration. The transition to the non-stationary phase occurred after the end of the co-current flow or after the arrival of reflected shock waves moving towards the flow.

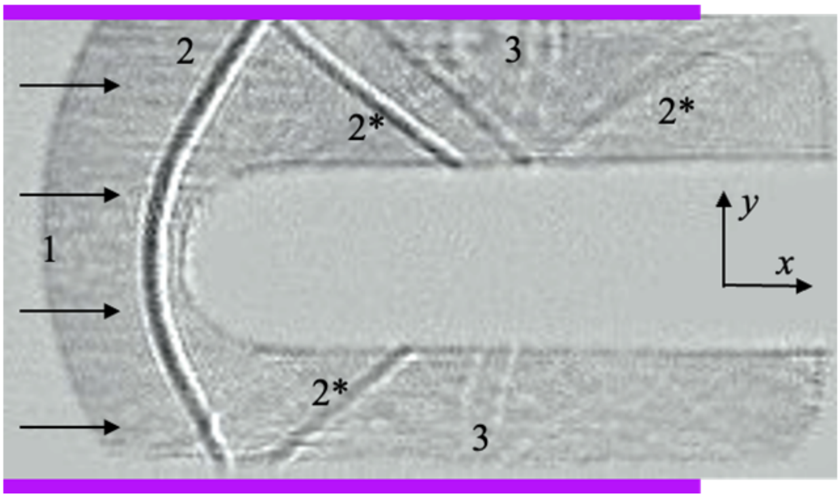


Fig. 2. Shadowgraphy image of supersonic flow elements around a streamlined body: 1 — flow, 2 — bow shock wave, 2* — inclined shock waves, 3 — position of separation zone. Flow Mach number is 1.60, density is 0.10 kg/m^3. The region of applied pulsed voltage is highlighted in color.

Fig. 2 shows a shadowgraphy image of the flow around a body at the steady stage of flow, including the bow shock wave, oblique shock waves, reflected shock waves from the channel walls and from the body. These shock waves interacted with the boundary layers formed on the walls of the discharge chamber.

Surface sliding discharge radiation in inhomogeneous supersonic flows

The glow of the surface sliding discharge in quiescent air is relatively uniform, with some filamentation appearing with gas density increase (Fig. 3a). The discharge glow distribution in supersonic flows shows a distinct correlation with the gas-dynamic structure of the near-surface flow (Figs. 3b–d). Local radiation of the discharge plasma is associated with the local concentration of excited gas molecules [9, 13], which depends on the electron concentration and, accordingly, the magnitude of the reduced electric field E/N (E is the electric field strength, N is the concentration of gas molecules) [13]. Photo images of the glow instantly visualize the flow structure. Fragments b, c, and d of Fig. 3 show images of the discharge glow initiated at various stages of the supersonic flow around the body.

All of the images show a curved line of intersection between the discharge plane and the bow shock of the streamlined body. This line separates the region of uniform glow in the flow from the high-density region behind the bow shock, where no glow is observed. At each point of the near-surface air layer, electron avalanches develop simultaneously and high-energy electrons excite nitrogen molecules that emit photons. In the high-density region, ionization does not occur, and glow is absent.

At the initial stage of flow formation (Fig. 3b) clearly visible the region of intersection between the bow shock in front of the body and the boundary layer. In this area, the discharge glow has a characteristic rounding that followed by a region of absent glow. A bright glow in the right part of the image appears in the separation zone at the edge of the discharge gap. At this stage the boundary layer on the walls of the discharge chamber remains laminar (Fig. 3b); at later stages the flow becomes turbulent [14]. Boundary layer state affects the glow characteristics of the surface sliding discharge, as seen in the uniform flow upstream (Fig. 3g, left). The boundary layer state also influences the formation of a low-density region due to interaction with an oblique shock wave with intense discharge glow is observed in the right part of the image (Figs. 3b–d).

The area without discharge glow becomes wider which corresponds to the stationary flow pattern observed in the shadowgraph images (Figs. 3c, d). The bright discharge glow region is located in a low-density zone formed by the interaction of an oblique shock wave with the turbulent boundary layer [7, 15]. The transition to the unsteady gas-dynamic regime is characterized by changes in the position and shape of the bow shock. The glow distribution in the flow region upstream of the body also changes and the discharge glow in the separation zone is modified.

Comparison of the shadowgraphy frames with discharge glow images demonstrates a clear relationship between the location of gas-dynamic inhomogeneities and the spatial glow distribution of the surface sliding discharge plasma. In flows with sharp density gradients the ionization rate increases in regions of low density concentrating the discharge current in localized channels [7, 15]. Low-density areas in the boundary layer are effectively visualized accordingly by the glow of the surface sliding discharge. Thus, the spatial glow distribution of the surface sliding discharge serves as a "map" of the near-surface flow structure: the plasma emission is intense in regions of rarefaction or strong density gradients associated with gas-dynamic structures in the supersonic flow.

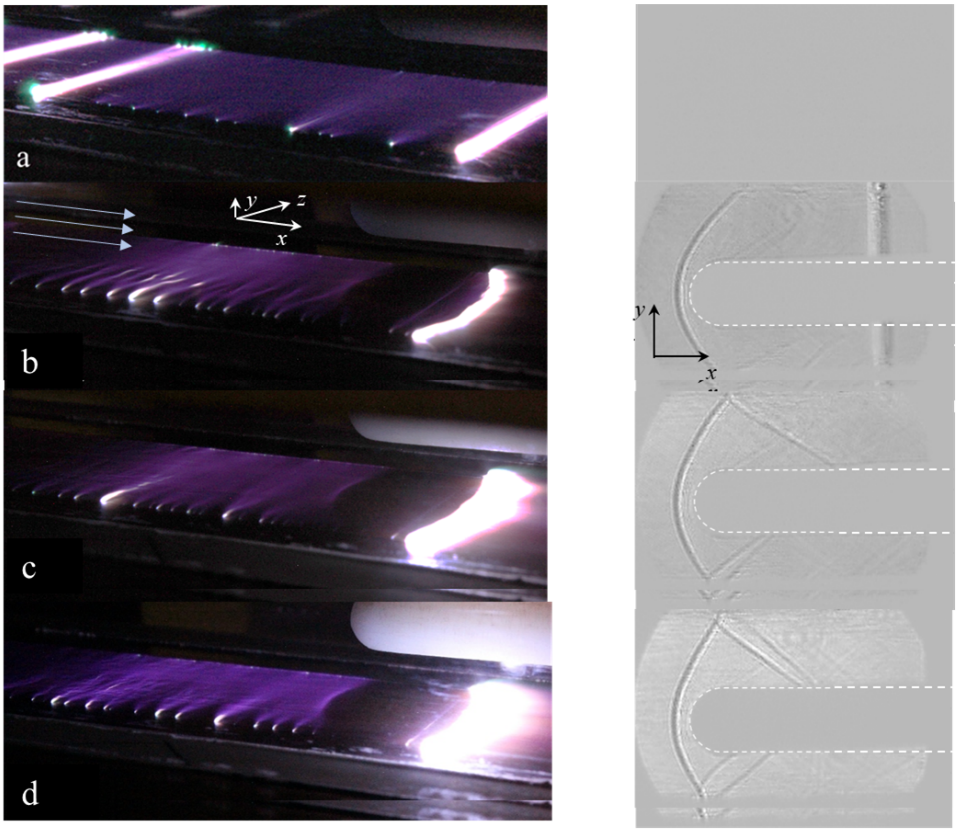


Fig. 3. Surface sliding discharge glow (left) and corresponding shadowgraphy images of the flow field (right) in quiescent air (a) and in supersonic flows with Mach number 1.54 (b–d). Air density is 0.09 kg/m³. Discharge initiated 31 µs (b), 42 µs (c), 54 µs (d) after shock wave diffraction.

Discharge Radiation of a Nanosecond Volume Discharge in a Supersonic Flow around a Model

The discharge radiation of the nanosecond volume discharge in still air exhibits a high uniformity [11, 13]. A series of photo images of the discharge glow in supersonic flows around the model (Fig. 4) enabled analysis of its spatial distribution, which is correlated to the specific features of discharge current. The volume discharge radiation in the uniform freestream supersonic flow remains largely homogeneous. However, the radiation is absent in the volume between the bow shock wave and the nose of the model. Further downstream, the intensity of the volume discharge radiation noticeably decreases. The distribution of surface sliding discharges glow in the near-wall regions also shows nonuniformity. The surface glow remains uniform upstream of the bow shock front; it disappears in the area of increased density immediately behind the bow shock and becomes more intense in areas where oblique shock waves interact with the boundary layer (Figs. 4 and 5). Thus, the spatial distribution of discharge radiation effectively visualizes the density field in the flow. Regions of lower gas density, where the electron concentration is correspondingly higher, produce more intense radiation, whereas areas of higher density are characterized by reduced discharge emission intensity.

Digital processing of the discharge photo images has demonstrated that the radiation distribution enables highly accurate determination of the position and shape of the bow shock front, as well as other features of the shock-wave configuration.

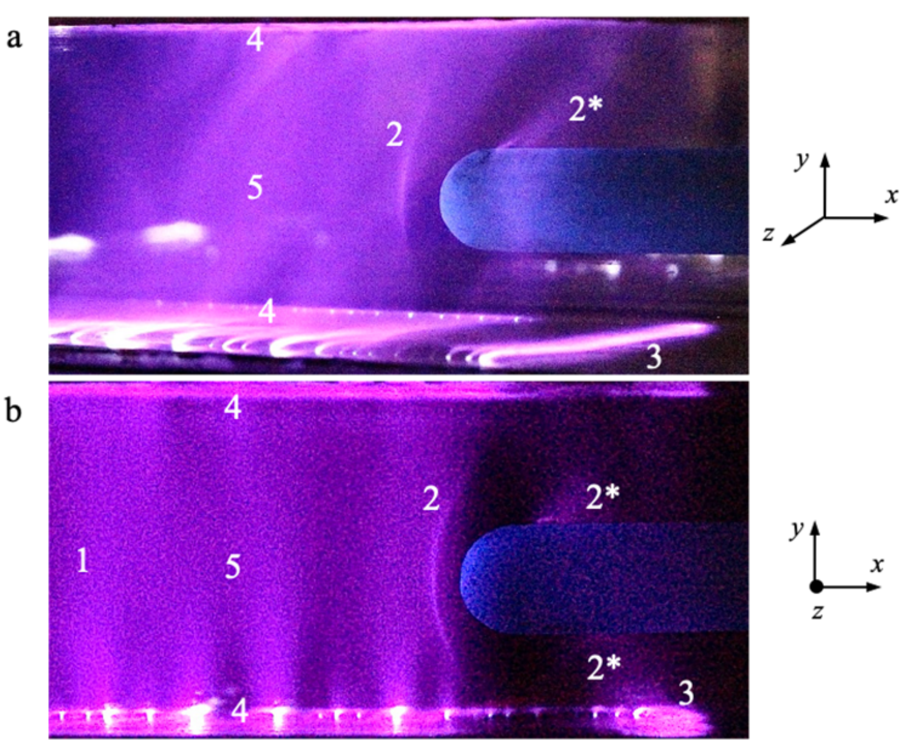
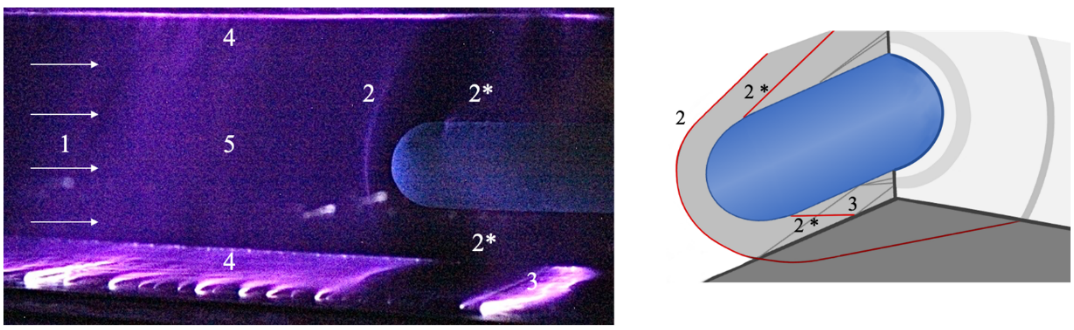


Fig. 4. Photo images of discharge during steady supersonic flow around the model at a Mach number of 1.55 (density 0.07 kg/m³), captured from different viewing angles.

Figure 5, a present a photo image of the nanosecond volume discharge at the steady stage of supersonic flow around the body. The spatial distribution of the discharge radiation is clearly linked to the shock-wave configuration illustrated in the three-dimensional flow diagram around the axisymmetric model (Fig. 5, b). The bow shock smoothly envelopes the body while a system of oblique compression waves develops around it, including waves reflected from the channel walls and the surface of the model. These flow structures remain stable during the steady stage when the discharge was initiated and its glow was recorded (Fig. 5, a).

A homogeneous distribution of volume discharge radiation is observed in the uniform supersonic flow upstream of the bow shock, which clearly visualizes the curved front of the shock wave. However, the volume discharge glow is absent in the region between the bow shock and the oblique compression waves. The intensity of the volume glow decreases further downstream in the flow separation zone.



a b

Fig. 5. Photographic image of discharge radiation during steady-state supersonic flow around the model at a Mach number of 1.52 (density 0.09 kg/m³) (a), and three-dimensional flow scheme around the axisymmetric model (b): 1 — airflow; 2 — bow shock wave; 2* — oblique shock waves; 3 — flow separation zone; 4 — sliding surface discharges radiation; 5 — volume discharge radiation.

Sliding surface discharges glow on the upper and lower walls visualizes the flow within the boundary layers and in regions where oblique compression waves interact with the boundary layer. In these areas, lower gas density is accompanied by higher electron concentration, resulting in intensified surface discharge radiation. As turbulence develops within the boundary layers, local density fluctuations near the walls lead to increased glow intensity in low-density regions (Fig. 5, *a*). Therefore, the spatial distribution of discharge glow is highly sensitive to small-scale flow inhomogeneities.

Discussion of results

Photo recording of the glow of nanosecond surface sliding discharge and combined volume discharge in supersonic air flows showed good prospects for visualizing the structure of supersonic flows in a channel. Recording of discharges radiation with ICCD camera with nanosecond resolution showed that the duration of the glow of the volume phase of the combined volume discharge does not exceed 300 ns, and the afterglow of surface sliding discharges can last up to 1000 ns. With such exposure times of photo images, the flow elements do not have time to shift, which allows visualizing the structure of the shock-wave configuration in front of the streamlined body instantly.

Comparison of photo images and shadowgraphy images provided information for revealing the three-dimensional structure of the flow. Gas discharge visualization by the volume discharge allows obtaining information about the structure of the flow in volume, unlike two-dimensional shadowgraphy images. Since the total plasma volume emits radiation, registration can be carried out at different angles and from different perspectives. This allows restoring a three-dimensional picture of the supersonic flow and identifying details that cannot be determined by classical optical methods. This approach is especially valuable for analyzing complex gas-dynamic structures, such as areas of interaction of shock waves, separation zones and turbulent formations in the flow.

Conclusion

An experimental study of a non-uniform supersonic flow in a channel around a blunt body was carried out by recording the radiation of a surface sliding discharge and a combined volume discharge of nanosecond duration and by the direct shadowgraphy. It was shown that the mode of the discharge current and the spatial distribution of the glow of a nanosecond surface sliding discharge are closely related to the gas-dynamic structure of the near-surface non-uniform flow. The discharge current can be localized in areas of low density, mainly in the zones of interaction of shock waves with the boundary layer. The correlation between the discharge glow and the position of shock waves, inclined shock waves, and boundaries of separation regions demonstrates the possibility of using a pulsed surface sliding discharge as a diagnostic tool for visualizing near-surface gas flows. The spatial distribution of the glow of a surface sliding discharge allows visualizing turbulent structures in the boundary layer of a supersonic flow.

The use of a nanosecond combined volume discharge for an optical diagnostic has shown its high efficiency in studying the spatial structure of a supersonic flow. A complex method combining the recording of discharge glow and high-speed shadowgraphy has made it possible to obtain detailed information on the flow structure, including shock waves, oblique shock waves, and areas of their interaction with boundary layers. The results of the work confirm the prospects for further use of these methods in plasma aerodynamics and can contribute to improving approaches to diagnostics and control of supersonic flow around bodies.

The obtained experimental results also make it possible to make clear the mechanisms of the relationship between the characteristics of nanosecond discharges with the local structure of high-speed flows and shock-wave configurations, as well as to determine ways to optimize new-generation plasma actuators.

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