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SUPersonic FLOWS WITH BOW SHOCKS VISUALIZATION WITH TRANSVERSAL DISCHARGES

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ABSTRACT:
Two similar configurations of low density supersonic flows with bow shock waves at cone-shaped obstacles are visualized. Shock tube with discharge camera and system for obtaining gas clusters were tested and 2 different discharges were used for flow visualization. Stationary and non-stationary flows were tested, short and long expositions were used. Short exposition is necessary to record instant images of high speed non-stationary supersonic flow in shock tube; nanosecond volume discharge was used in this case; plasma redistribution in the flow with discontinuities was instantly visualized. Long exposition is needed to record a stationary weakly glowing micro nozzle jet flow spreading into a high vacuum region and interacting with a skimmer. The CFD simulations reproduce the visualized flow pattern and provide better understanding of the flow.

1 Introduction
Many flow visualization methods have been developed using different physical phenomena and digital technologies. They are widely used in basic researches in gas dynamics as well as in practical applications. Their descriptions can be found for example in reviews. Nevertheless, not all visualization methods are appropriate for supersonic flows of rarified gas. Optical techniques such as shadow and schlieren imaging are known to show good results for supersonic flow visualization and do not affect the flow structure, but they demand additional equipment and special construction of vacuum chambers. Since they are actually based on measuring deviation of refractive index with variation of absolute number of atoms in a volume, they are often lacking in sensitivity in case of rarified gases [1]; dense media is preferable for their implementation. Methods using tracking seeded particles are not applicable as they are not compatible with vacuum conditions and pumping systems. Besides, low gas pressure flow results in its specific interaction with seeded particles, so they do not represent streamlines in the right way [2].
Supersonic gas flow structure may be visualized through the media luminescence registration [3,4]. Optical emission appears in the high-enthalpy gas flow; at gas excitation by external radiation or particles. Also the gas flow structure may become a source of optical radiation at electric current passage through the gas (electroluminescence phenomenon). The energy necessary for
electroluminescence is initially converted from outward electric field to atoms and molecules of the gas through bombardment by electrons, which are accelerated in the electric field. The effect of media radiation occurs at external electric field $E$ values $eE > U_i$, where $U_i$ is the gas molecule ionization potential; $e$ is electron charge, $l$ – mean free paths of the electrons.

Some simple gas discharge visualization techniques use flow glow registration by different types of gas discharges. When initiating discharge in a gas flow, density inhomogeneities of the medium lead to redistribution of the radiation intensity. This effect was used for visualization of stationary supersonic flows [5,6] in wind tunnels at low pressures. The method advantages are: the simplicity of hardware design and the possibility of observing dynamic changes in flow pattern during the experiment. Under average gas pressures ($P=1-10$ kPa), typical for many problems, the non-homogeneity of the flow density leads to redistribution of the electric current in flow due to the strong dependence of the electron concentration and conductivity on the magnitude of the ionization coefficient. It depends on nonlinear function of $E/N$ ($N$ is concentration of heavy particles). There are various low temperature plasma effects associated with density gradients. They depend on the ratio of the linear scale of the particles concentration gradient to different ionized gas physical scales (Debye radius, electrons free path length, etc.). The gas discharge visualization is usually used to determine the shape of discontinuities, inhomogeneities, streamlines direction.

The problem of the present paper is to visualize two similar configurations of low density supersonic-transonic flows with bow shock waves at cone-shaped obstacles. Two supersonic devices were used and 2 different visualizing discharges. Stationary and non-stationary flows were tested, short and long expositions were used. Short exposition is necessary to record instant images of high speed non-stationary supersonic flow near a cone in shock tube. Nanosecond volume discharge with pre-ionization by plasma sheets was used in this case; plasma redistribution in the flow with discontinuities was visualized with nanosecond time resolution. Long exposition is needed to record a stationary weakly glowing micro nozzle jet flow spreading into a high vacuum region and interacting with a skimmer. Visualization it is needed for revealing structure of the jet flow in gas cluster equipment [7].

In both cases, the main element to be visualized was a conical shaped bow shock wave forming near the tip of the cone at local supersonic flow velocities. In Both cases flow structure was visualized due to electroluminescence effect using discharge with electric field transversal to flow direction. Nevertheless, the physical origin of the glow images differs due to difference of the discharges current time. In the first case, low density areas in front of shock wave has more intense glowing. In the second case, luminosity intensity is proportional to media density, and the glowing is more intensive behind the shock.

2. Pulse discharge in a shock tube

A shock tube combined with a special discharge chamber was used to study shock waves diffraction on cone and discharge ionization of the arising gas flow. The setup configuration is shown in the Fig. 1. The shock tube and an electric discharge chamber have a rectangular profile 24x48 mm. The tube can generate shock waves with Mach numbers $M = 1 – 5$, using helium as the driver gas and air as the driven one. Pulse volume discharge with ultraviolet preionization by radiation from the sliding surface discharges was used for flow ionization and testing of visualization methods. The sliding discharges initiated on the top and bottom surfaces of the chamber and have size of 100x30 mm. High initial volume discharge homogeneity is obtained thereby. The sidewalls of the test chamber are made of quartz glass to make the discharge glow and the gas flow visible. The pressure was controlled by pressure gauges; a special synchronization scheme was developed to switch the discharge initiation on the different stages of shock wave interaction with a cone in the discharge chamber. Flow spectrum
analysis showed that the main source of the luminescence is the nitrogen gas second positive band N++. Duration of the discharge was analyzed with CCD cameras with nanosecond gate duration and it had been shown that in a motionless gas, the glow intensity decays in 100-200 ns depending on the pressure.

In a structured flow plasma glow is redistributed to the zones of high E/N: vortices and shock waves [8-10]. It was possible to record the integral nanosecond-lasting discharge glow distribution by photo cameras (Fig. 1). Instant flow images were thus obtained as soon as gas flow does not actually move in exposition time of 200 ns.

The cone model was made of a dielectric material half- angle was 30°, it was developing into a cylinder with a diameter of 10 mm (Fig. 1). Pulse discharge was switched on in different moments of shock wave interaction with the cone. 2 glow images were recorded through opposite windows of the test camera in every experiment. Instant glow image of initial stage of shock wave interaction with cone is on Fig.2a; shock Mach number is 4,2. Discharge plasma glow is only in front of shock wave - in low density area, separated by the shock front. Fig 2b presents the image of a flow after shock wave had passed away and the flow behind it is ionized. Flow Mach number is 1,4. We can distinguish the attached bow shock wave (conical shock surface); reflected shock wave (a reflection of the bow shock waves from the upper walls of the chamber); the line of flow separation at the junction cone-cylinder; flow reattachment line; the high pressure area (dark zone) behind the bow shock surface. These elements are drawn in scheme in Fig. 2c.
It was possible to measure the angle of incidence of the bow shock with sufficient accuracy. The angles measurements were made by processing pairs of images obtained from 2 sides of camera and then the angle values were averaged. Plot presenting the dependence of the half-opening angle $\alpha$ in non-stationary flow – while shock diffraction on cone - is on fig 3.a. Fig 3.b presents angle $\alpha$ in the stationary flow depending on flow Mach number (formed behind the incident shock wave for $t>40$ ms). The dots indicate the experimental values of the bow shock wave half-angle $\alpha$. The solid line presents the CFD calculation for steady cone supersonic gas flow. With increasing the Mach number of the air flow, the angle of the shock wave decreases. The most of the experimental points agree well with the calculated data (steady flow, the minor effect of the chamber walls on the flow).
The method is not contactless strictly speaking – the high power discharge influences the flow – but it is the post discharge flow. During the discharge current the gas dynamics processes are launched [...] ut no changes happen during 200-300ns of electric current.

3. Glow discharge visualization of supersonic jet interaction with a skimmer

In the second experiment series, the structure of a gas flow from a supersonic nozzle adjacent to a conical skimmer was examined using a transversal glow discharge. Shock wave structure in this system is of great interest, because nozzle-skimmer construction is a part of the usual system of obtaining gas clusters. During adiabatic expansion of a working gas through a supersonic nozzle into a vacuum chamber, the expanded gas becomes cold enough for clusterization. A conical skimmer, aligned with the axis of expansion, removes a large part of the non-clustered gas and allows some fraction of the more forward-directed clusters to pass through. So, information on the properties of the jet below a nozzle is essential for optimization the nozzle and skimmer geometry and the distance between them. Nevertheless, we could not find any experimental information about influence of the skimmer on the flow structure. Only a few works on the free flow visualization from a supersonic micro nozzle under clusterization conditions are known [11]. Supersonic nozzle being tested is a component of a gas cluster condensation system [12]. The setup is typically used to obtain gas cluster ion beams of different gases in size range from 100 to 5000 atoms/cluster, accelerated by voltages up to 30 kV. The clusters are formed by gas condensation during adiabatic expansion from a conical supersonic nozzle into a vacuum chamber. The nozzle critical cross-section is 140 um; the length of diverging part and half-angle are 20 mm and 6°, respectively.

To perform the visualization, the upper cover of the chamber was made transparent. The working gas (Ne, Ar) was injected into the nozzle under pressure in range of 2 to 7 bar; the maximum pressure in the vacuum chamber was limited by performance of the pumping system and could not exceed 8·10⁻3Torr. To decrease gas load on the pumps, normally we use pulsed regime of working gas supply. Nevertheless, length of a gas pulse can be selected up to a few seconds, which is long enough to take a photo and is much longer than typical times of equilibrium setting in the discharge and in the gas flow, so the regime of visualization can be described in terms of steady discharge. In the presence of an obstacle, the regime of a flow with a bow shock wave near the obstacle is set if the flow is supersonic, otherwise the flow has now bow shock wave. In the experiments described, the obstacle was a hollow conical metal skimmer with the cone angle of 65°and an axial orifice having 0.5 mm diameter. The distance between the nozzle and the skimmer could be set from 0 mm to 80 mm by translational movement of the nozzle. Two plane copper electrodes were placed symmetrically with respect to the nozzle-skimmer axis on the distance 65 mm from one another. Their length equaled 62 mm. One electrode was supplied with DC voltage; the other was grounded as well as the nozzle and the chamber walls. Depending on the gas type and the pressure regime, optimal voltage for the visualization could be found. For low voltage, glow intensity of the discharge was insufficient. Otherwise, higher voltage lead to heavy luminescence of all the discharge volume, and the flow details could not be recognized. On a whole, applied voltage was in range from 0.3 to 2.5 kV, and the discharge current was limited by value 1 mA. So, the applied power deed not exceed ~1 W. At the same time, estimated power of the flowing gas well exceeded 30 W. Therefore, as it is much greater than the electrical discharge power, described visualization technique can be considered as contactless.

Typical pictures of supersonic jet encountering the skimmer are shown in Fig. 4. The distance between nozzle and skimmer is 4 mm, 26 mm, 37 mm, 46 mm consequently.

The visualization technique allows evaluation of supersonic jet geometrical dimensions and optimization of the nozzle and skimmer position and shape; the jet structure can be revealed well. We
should mention that even when the nozzle-skimmer distance was small and skimmer penetrated into Mach barrel, the visualized shape and structure of the flow upstream from the skimmer coincided with ones without skimmer, obtained by us with the same technique in [13]. So, the obstacle did not change gasdynamical nor electrical structure of the discharge near the nozzle dramatically.

If the distance between the nozzle and the skimmer was large enough, no bow shock could be recorded near the skimmer. It means that the flow is subsonic in this region. At decreasing the distance, conical shock wave appears which corresponds to the entrance of the skimmer into supersonic region. Nevertheless, the cone shock waves are not straight, but rather curved towards the skimmer, so, exact measurements of the shock wave angle are difficult. This can be explained by non-uniform cross-section of gas velocities distribution in jet structure: the velocity decreases with distance from the axis.

Beside the experiments, computer simulations of a viscous gas flow in the axisymmetric nozzle and jet were performed. The flow was modeled by the system of two-dimensional unsteady Navier–Stokes–Fourier (NSF) equations. The system was written out in the divergence form and supplemented by the equations of state of an ideal gas and the boundary conditions on the boundaries of the computational domain. Terms describing convective transport in this system were approximated using a modified Godunov's scheme of high order of accuracy [14]. Terms describing diffusive (viscous) transfer were approximated using the finite volume method, which in the case of a uniform grid is reduced to a central difference approximation of derivatives. Advance in time was performed using the third order Runge–Kutta method. Influence of the gas condensation on the stream parameters was not taken into account on this stage.
Since the expansion ratio in the nozzle and jet is high (more than 1000), and at inlet temperature, the temperature at the nozzle exit falls below the critical value. Therefore temperature dependence of dynamic viscosity $\mu$ is described with the modified Satherland expression. Possible effects of rarefaction near the solid surfaces were considered with slip boundary conditions and first order temperature jump near the wall [15]. As the result of the simulations maps of density, temperature, pressure and Mach numbers could be obtained. The maps revealed the similar flow configuration - Mach barrel behind the nozzle and bow shock waves at the skimmer as seen in the experimental glow images. Dash line shows the area of supersonic flow. Also we can see the flow CFD map inside the
skimmer changing with distance increasing. The separation zone near the wall is widening while the density on the axis does not change significantly.

**Conclusion**

Two types of transversal discharges were used for supersonic flows visualization near the cones in rarified gases. Flow structure was visualized due to electroluminescence effect in both cases. The discharge current and glow intensity were redistributed in the non-homogenous flow in both cases and conical bow shock configuration was visualized. Nanosecond volume discharge with pre-ionization by plasma electrodes was used in the shock tube for recording instant plasma glow images (discharge glow time exposition). The cone model was made of a dielectric material. Bow shock angles were measured in air flow with $M=1.5-1.7$.

Stationary glow discharge was used to visualize a stationary weakly luminous micro nozzle jet flow spreading into a high vacuum area and interacting with a conical metal skimmer. The aim was to reveal the structure of the jet flow in gas cluster equipment. A Mach barrel is visualized at the nozzle exit. The bow shock at the skimmer is curved towards the cone. The occurrence of bow shock allows determining the area of supersonic flow. The computational flow dynamics model based on Navier–Stokes–Fourier equations was verified by comparison with the experimental images and showed a good agreement with the observed flow structure. The physical origin of the images luminosity differs. In the first case low density areas in front of shock wave has more intense glow. In the second case luminosity intensity is proportional to media density – glow is more intensive behind the shock.

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