ULTRASENSITIVE GLOW DISCHARGE METHOD FOR VISUALIZING HYPERSONIC FLOWS OF RAREFIED GASES

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The proposed method of visualizing hypersonic flows of a rarefied gas employs the cathode luminescence of a glow discharge. It is shown that the method possesses high sensitivity and good spatial resolving power and may be used to study flows with slip and in the transitional regime.

Quite a number of methods have been proposed for obtaining photographs of hypersonic gas jets at low pressures. Apart from improvements in the refractometer both as regards its modernization and increasing the number of passages of light rays through the region being investigated [1, 2], the use has been proposed of such physical phenomena as spectral absorption [3], the weakening of corpuscular rays on their passage through a gas* [3–6] and the radiation accompanying such a passage [7–9], the afterglow of a gas [3, 10], and the luminescence of a gas excited by electrical discharges [2, 3, 11–13].

Discharge methods of visualization show to advantage compared with other methods in the simplicity of their apparatus, their freedom in practice from interference by vibration, thermal flows and diffraction, and the fact that preliminary complicated tuning is unnecessary. The defects usually associated with discharge methods are the difficulty of quantitative interpretation of photographs because the visualization mechanism is not completely understood, and the possible influence of the discharge on the hypersonic flow parameters.

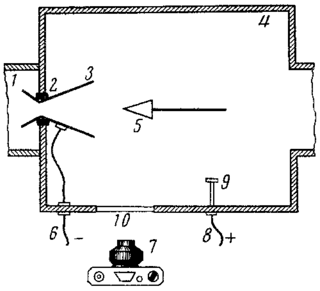

Fig. 1. Experimental set-up.

The method of visualization described below also employs the luminescence created by a glow discharge. This method preserves all the advantages of discharge methods while possessing high sensitivity. The elicited mechanism of visualization allows one to obtain not only high-quality photographs of hypersonic flows at low pressures, but also a definite method of interpreting them.

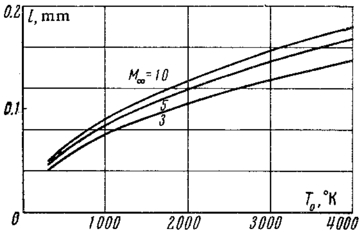

Fig. 2. l v. T_0 with m_∞ = 3, 5, and 10.

1. **Experimental set-up.** In the application of glow discharge to visualizing hypersonic flows the choice of the position and polarity of the electrodes in the working section of the aerodynamic tunnel is of great importance. The most favorable region of a glow discharge for visualization purposes would appear to be the uniformly luminous positive pole of the discharge. However, when the pressure falls to 10 N/m^2 and lower, the intensity of luminescence of the positive pole falls and becomes insufficient for taking visible pictures [3]. As the pressure falls the zones of luminescence around the electrodes are enlarged. What possibility is there of using the aerodynamic model as one of the electrodes?

In [11] the application of a model as an anode is described. However, reduction of the pressure to 1 N/m^2 leads to an intense growth of anode luminescence in the immediate neighborhood of the anode (the model) and a picture of the model shock is masked by this luminescence.

In [2] the application of the model as a cathode in the discharge is described. The deficiency of this method lies in the difficulty of examining the picture obtained because the boundary of the dark cathode region is superimposed on the model shock wave. In addition the model is rather strongly heated in this case, which leads to thermal disturbance of the flow. Thus, the use of the model as one of the electrodes in the discharge serves no useful purpose.

When the pressure is lower than 10 N/m^2, the main radiating zone of the discharge becomes the region of glow discharge. Therefore the application of this region of the discharge for visualization of nonuniformities of density in hypersonic flow at low pressure appears the most promising. In Fig. 1 is set out our chosen experimental scheme for utilizing the glow discharge. Gas from the inlet 1 passes through the nozzle 3 into the working section 4, accelerating as it

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*G. A. Bogdanovskii, L. N. Malakhov, and A. V. Balakov, "Electronic-televisor method of investigating nonuniformities in low-pressure gas flows," Author's Certificate no. 140125, 1960.

does so to hypersonic speeds. In the working section the hypersonic jet flows past the model 5. The hypersonic nozzle 3 acts as the discharge cathode and is insulated from the working section 4 by a dielectric washer. The anode 9 is placed outside the field of view in the depths of the working section. Voltage is supplied through the conductors 6 and 8. The model and walls of the working section are at a floating potential in the discharge. A rectifier on 2–3 kV serves as the discharge power supply. During the discharge the inner cavity of the nozzle and the flow region downstream of the nozzle are filled by a glow discharge, and the hypersonic flow and shocks illuminated by it are observed or photographed 7 through the window 10 in the wall.

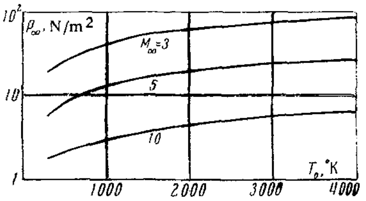

Fig. 3. Regions of p_∞ and T_0 values where $\tau_1/\tau > 1$, when $M_\infty = 3$, 5, and 10.

2. Fundamental characteristics of a glow discharge in a hypersonic air flow. The voltage drop over the discharge gap when the pressure ranged from 10 to 10^{-1} N/m² was approximately 370 to 500 V. The current strength of the discharge did not usually exceed 10 mA. Thus the selected discharge power did not exceed a few watts. The current-voltage characteristic of the discharge falls as is typical of a glow discharge with a normal cathode drop.

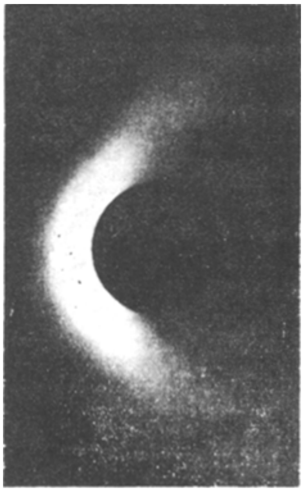

Fig. 4. Flow about a cylinder when p_∞ = $= 0.23$ N/m², $M_\infty = 7.4$, $R_\infty = 52$, $K = 0.2$.

The glow discharge used to observe the hypersonic jet and shocks is violet in color. Study of the spectrum of this radiation has shown that it belongs to the first negative system of molecular nitrogen N_2^+. The intensity of the zones of the first and second positive systems of neutral molecular nitrogen is negligible. If the effects of excitation of the first and second positive and first negative systems of nitrogen [14, 15] are taken into consideration one may conclude that the luminescence is excited by electrons with energies of the order of 50 eV and higher. In addition slow electrons may be present with energies of the order of a few eV. This deduction is confirmed by the results of probe examinations and of measurements of the energy distribution of the electrons by the retarded potential method. Thus the electrons are revealed to have for the most part the same energy level. This energy turned out to be close to the magnitude of the cathode drop.

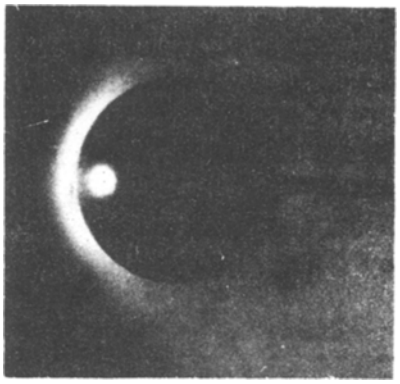

Fig. 5. Flow about a sphere when p_∞ = $= 0.23$ N/m², $M_\infty = 7.4$, $R_\infty = 97$, $K = 0.11$.

From the main experimental results obtained one may draw conclusions about the mechanism of visualization of nonuniformities of density in an air flow using the nozzle as cathode of the glow discharge. In addition to its usual function of accelerating the gas to hypersonic speeds, the nozzle acts as a source of an electron beam with energies of the order of the cathode potential drop. The axis of the beam, assuming the nozzle is axisymmetric, coincides with the nozzle axis. When electrons and gas molecules collide inelasticially ionization and excitation of the molecules occur. Because the excited ions N_2^+ radiate spontaneously, the diffusion region of the electron beam shines. A local variation in gas density is accompanied by a variation in the number of collisions between electrons and gas molecules, which leads to a variation in the intensity of luminescence. In this way nonuniformities of density are visualized. As a result of diffusion in elastic and inelastic collisions, the electron concentration diminishes with distance from the nozzle. The intensity of luminescence is also attenuated. With a decrease of gas density the degree of attenuation is also decreased, and the luminescence occupies a bigger region downstream of the nozzle. Thus visualization of the hypersonic flow and model shock waves is ensured over a wide field of view.

As already mentioned, the power dissipated in the discharge is very small in this method. Probe investigations have shown that the concentration of high-energy particles is no more than $10^{-4}\%$. Thus the discharge could be expected to have an insignificant influence on flow parameters. Indeed measurements made by thermocouples, replacing the model in the hypersonic flow, revealed that a current strength of 2–10 mA induced increases in the recorded temperatures of 0.4–0.7%. Obviously, such a temperature variation can be neglected.

3. Spatial resolving power of the method. The first negative system of nitrogen bands, which makes the visualization possible, originates in the state $X^2\Sigma_g^+$. The average lifetime of this state is finite and equals $6.5 \cdot 10^{-8}$ sec [16]. Let us consider what limitation this sets on the use of the method described.

For high-speed gas flows, when the excited particle is able to move a noticeable distance during the time interval between excitation and radiation distortion of the true flow picture may occur. When the flow speed is u, the particle covers during the average lifetime of the excited state τ a distance $l = u\tau$. Thus the effective spatial resolution is determined by l. Expressing the flow speed u in terms of the stream Mach number M_∞ and the stagnation temperature T_0, we obtain

$$l = 1.3 \cdot 10^{-3} \left(T_0 \frac{5M_\infty{}^2}{5+M_\infty{}^2}\right)^{1/2}. \tag{3.1}$$

Here l is expressed in mm, T_0 in °K. In Fig. 2 is shown the variation of l with T_0 when $M_\infty = 3$, 5 and 10. One can see that, when the stagnation temperature is of the order of 1000° K and less, the spatial resolution is not worse than 0.1 mm. Only when $T_0 = 5000°$ K and the Mach number equals 10 does l reach the value 0.2 mm. Such a spatial resolution can be considered good. For example, when a hypersonic stream is probed by a thin focused electron beam, the limit of resolution is fixed by the beam diameter, which is 0.3–0.5 mm.

Since the excited particle is ionized, during the average lifetime of the excited state it is moved by an electric field through a distance whose magnitude and direction will depend on the field strength vector. However, it is not difficult to show that this distance will be comparable with l only when the field is of the order of 100 V/cm. Even in the glow discharge region, where all of the processes considered occur, such a value is obviously not reached.

Possible processes due to gas-kinetic collisions of excited ions N_2^+ with surrounding particles may also be neglected if $\tau_1/\tau > 1$, where τ_1 is the period of the gas-kinetic collision. The smallest value of τ_1 is likely in the most dense region of the gas, i.e., behind the straight part of the model shock. Let us estimate τ_1/τ in this region. By definition $\tau_1 = \lambda/\nu$, where λ is the mean free path between gas-kinetic collisions and ν the mean molecular speed. Assuming a Maxwellian distribution of molecular speeds and expressing λ and ν behind the shock in terms of the free-stream static pressure p_∞, the Mach number M_∞, and the stagnation temperature T_0, we obtain

$$\frac{\tau_1}{\tau} = 1.6 \cdot 10^2 f_1(T_0)\, f_2(M_\infty) \frac{1}{p_\infty}, \tag{3.2}$$

$$f_1(T_0) = T_0{}^{1/2}(1 + C/T_0)^{-1}, \qquad (3.2)$$

$$f_2(M_\infty) = (7M_\infty{}^2 - 1)^{-1}\left[5M^2_\infty/(5 + M_\infty{}^2)\right]^{-1/2}. \qquad \text{(cont'd)}$$

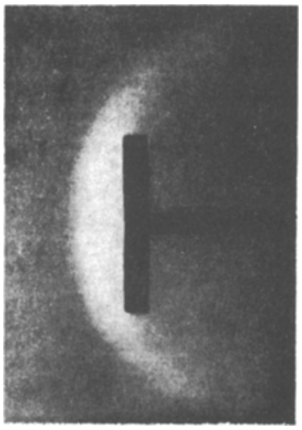

Fig. 6. Flow about a disc when $p_\infty = 0.32$ N/m^2, $M_\infty = 8.33$, $R_\infty = 170$, $K = 0.07$.

Here C is Sutherland's constant, T_0 is expressed in °K, p_∞ in N/m^2. The curves plotted in Fig. 3 relate T_0 and p_∞ according to (3.2) for $\tau_1/\tau = 1$ and Mach numbers $M_\infty = 3$, 5, 10. The requirement $\tau_1/\tau > 1$ is satisfied in the range of T_0 and p_∞ values lying below these curves.

Thus the finite lifetime of the excited state of N_2^+ does not put a noticeable limitation on the application to the study of rarefied gas flows of the glow discharge method with the nozzle as the cathode.

4. Production of the visualization pictures. The photographs were taken with a "Zenit" mirror camera. Since the density gradients in the flow region investigated are not large, it is appropriate to use films with a high gamma. The author used "MZ" film with a γ of about 1 or "Mikrat" with a γ of 2.5–3. Depending on the flow parameters, the scale of the image, and the film, the exposure varied from a few seconds to a few minutes. Figures 4–6 are some of the air flow photographs obtained. The flow parameters—static pressure p_∞, Mach number M_∞, Reynolds number R_∞, Knudsen number K—are shown in the figure captions. The Reynolds number R_∞ is expressed in terms of free-stream conditions. The model radius was taken as the characteristic dimension in calculating the Reynolds and Knudsen numbers.

In the photographs shock waves are clearly visible. The region of increased density at the model, as is characteristic of rarefied gas flows, is quite diffuse. The flow about a disk is shown in Fig. 6. In spite of the fact that the disk radius was quite large (17 mm), the shock was curved. The shock is straight only in the region of the stagnation point. This phenomenon is also characteristic of a rarefied gas flow. In the usual classification of rarefied gas flows, the flow in Fig. 6 refers to a flow with slip, while Figs. 4 and 5 show flows in the transitional regime between flows with slip and the free-molecular regime.

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