EXPERIMENTAL STUDY OF VORTEX FLOW ABOUT LOW ASPECT RATIO WINGS AND CIRCULAR CONES
AT M = 2

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ABSTRACT: Characteristic of the flow about wings of low aspect ratio with subsonic leading edges and bodies of revolution at angles of attack is the formation of spiral vortices as a result of rolling-up of the transverse flow, which separates near the wing leading edge and on the lateral generator of the body. The vortices, concentrated in a pair of free vortex cores, interact with the boundary layer, causing a complex flow pattern on the surface of the model in question.

There are several methods which make it possible to study the flow about the model. Pickups may be used to measure the pressure field or the velocity field near the model. This technique has found wide application and was used for studying the flow pattern about wings and bodies of revolution at both subsonic and supersonic speeds (see, for example, \cite{1-4}). However, this method is very tedious and, in addition, the probes always introduce disturbances into the flow, particularly for supersonic speeds.

A visual picture of the vortex flow may be obtained in a towing basin by adding to the water metal powder in the suspended state, or by introducing filaments of colored liquid \cite{1, 6}.

The vapor screen \cite{5} and smoke \cite{3} methods are also used for flow visualization.

The boundary layer flow on the model may be studied with the aid of oil or evaporating coatings. These methods have been used in \cite{1, 7} to study flow about wings and in \cite{8} to study flow about circular cones.

According to the studies presented in \cite{9} of an electric discharge with the application of high voltage to electrodes located in an air stream, a stable glow occurs as a result of the prebreakdown discharge.

The properties of the prebreakdown discharge have been used by the authors of the present paper to study visually the vortex flows (high voltage electric discharge method). This technique was used to obtain the trajectories of the vortex trails for low aspect ratio wings and circular cones mounted at various angles of attack in a stream with Mach number $M = 2$ and Reynolds number $R = 0.9 \, \times \, 10^6$.

§1. Method for visualizing nonhomogeneities of supersonic flow.

The method of visualizing nonhomogeneities in a supersonic flow is based on the use of the properties of the prebreakdown discharge, described in \cite{3}. That study indicates that if a high voltage is applied to electrodes located in a supersonic flow a stable glow will occur between the electrodes, which serves as a background against which the shock waves from the electrodes and the flow separation region are clearly seen. The prebreakdown discharge differs considerably in its characteristics from the glow discharge, which is usually used for visualizing flows of a rarefied gas.

The spectrum of the prebreakdown discharge, which is the result of the electronically excited nitrogen molecules, is filled with bands of the second positive $N_2$ system. The excitation functions of the $N_2$ bands have a clearly defined threshold nature as a function of the energy of the exciting electron, as shown in Fig. 1 [10].

The nonhomogeneity of the supersonic gas flow may be analyzed by using the pattern of the electron cloud drift under the influence of the electric field.

The drift rate and the average energy of the electrons are usually defined as function of $E/pV/cm$-mm Hg. By $p$ we mean the pressure referred with respect to density to the normal temperature 0°C; $E$ is the electric field intensity.

The latter is particularly important in the case of supersonic flow, since the densities may differ significantly for similar static pressures.

The electron cloud drift velocity $u_0$ in nitrogen may be determined from the data of \cite{11}. For values of $E/p$ from 16 to 15 $V/cm$- mm Hg with a flow velocity $V = 5 \times 10^4 m/sec$, which is the case for the experimental conditions used below, $u_0 \approx 5 \times 10^4 - 6 \times 10^4 m/sec$, i.e., $u_0 > V$.

This situation permits neglecting the gas motion velocity in considering the electron drift. Under the same conditions the drift velocity for positive ions is $u_i \approx 10^6 m/sec$.

In accordance with the quasi-neutrality condition, the number of ions is equal to the number of electrons $n_0 = n_i$. The current density $j = n_e u_e + n_i u_i$; in addition, $u_e > u_i$; therefore we can with an adequate degree of accuracy assume that $j = n_e u_e$.

From this relation we can estimate the average electron concentration. For $E/p = 10 V/cm$-mm Hg, $I = 0.05 A$, $S = 1 cm^2$ we have $n_e \approx 10^{17} - 10^{18} cm^{-3}$. This value may be used to estimate the form of the electron distribution with regard to energy.

A necessary condition for the existence of the Maxwellian with respect to velocity is the coincidence of the times between electron-electron and electron-molecule collisions. In addition, these times must be small in comparison with the time of electron passage through the interelectrode gap [11].

An estimate of the mean time $\tau_{ee}$ between electron-electron collisions may be made using the Spitzer formula [12]:

$$\tau_{ee} = \frac{0.267 \lambda_e}{\lambda_e} = \frac{\lambda_e}{\lambda_e} - \frac{\ln \lambda_e}{\frac{12 m_e m_e}{e^2 \hbar}}.$$  

Here $\lambda_e$ is the electron temperature; $\lambda$ is the Coulomb logarithm.

The electron-molecule collision time for the electron mean free path $\lambda_e$ is:

$$\tau_{em} = \frac{1}{\frac{1}{\lambda_e} - \frac{1}{\lambda_e}} = \frac{m_e u_e}{E E_e}.$$  

To calculate these times we need to know the temperature $T_e$ of the electron gas. To estimate the temperature of the electron gas we can use the results of \cite{11}, in accordance with which the expression for the electron mean energy $\epsilon_e$ and the mobility $\mu_e$ (as a function of the energy acquired by the electron over the mean free path, $E E_e / (v e)$) have the form (here the momentum transfer section $Q_e$ is considered constant):

$$\tau_e = 0.427 \left( \frac{m_e}{m_e} \right) \frac{Q_e}{\mu_e} \frac{E E_e}{u_e} \frac{u_e}{v_e} = 0.634 \left( \frac{m_e}{m_e} \right) \left[ \frac{2 E E_e / u_e}{\sigma_e} \right]^{7/6}.$$  

Hence

$$\tau_e = \frac{0.427 m_e a v_e}{2 (0.634)^{1/6}}.$$  

Here $m_e$ is the mass of the gas molecule; $m_e$ is the electron mass. Substituting the corresponding numerical values, we obtain $\epsilon_e \approx 5 eV$.

Noting that a temperature of 11 600° K corresponds to the mean electron energy of 1 eV, we have $T_e \approx 60 000° K$.

If the relation is valid only for the estimate, since we have not proved the existence of a Maxwellian distribution of the electrons with respect to energy.

Substituting the value of $T_e$ into the expression for $\tau_{ee}$, we obtain $\tau_{ee} \approx 5 \times 10^{-3} sec$.

On the other hand, the time between electron-molecule collisions is of the order $\tau_{em} \approx 10^{-12} sec$. Thus, the frequency of the electron-molecule collisions exceeds considerably the frequency of the electron-electron collisions. On the other hand, the time for the electron to travel the inter-electron distance $L \approx 30 cm$ is equal to $L / v_e = 4 \times 10^{-6}$ sec, i.e., less than the time for collision between electrons.
Consequently, the electrons which are emitted by the cathode as a result of auto-electronic emission reach the anode practically without mutual collisions, experiencing in this case only collisions with the air molecules.

If the nonhomogeneity in the gas has the form of a filament with reduced density, stretched out along the flow and along the lines of force, then in this case an increase of the current density must be observed in this nonhomogeneity. Actually, since the intensity of the electric field may be considered constant both near the nonhomogeneity and in the nonhomogeneity itself, the quantity $E/p$ will differ significantly in these regions. In accordance with this the drift velocity of the electrons within the gaseous nonhomogeneity will also differ. The electron concentrations $n_e$ both outside and within the gaseous nonhomogeneity must be similar from the condition of the absence of a space charge. This is associated with the fact that for field intensities $E/p$ from 10 to 15 V/cm-mm Hg, which are realized under the considered conditions, when an electron travels through the interelectrode gap the probability of ionization of a gas molecule by the electron is a quantity of order $10^{-14}$ [10]. In other words, the number of secondary electrons and, consequently, ions which are formed as a result of ionization of the air molecules by the electrons does not exceed about 1%.

From this analysis we can conclude that the electron distribution differs significantly from Maxwellian; the number of secondary electrons formed in the discharge is small, so that the electrons emitted by the cathode move practically along the lines of force of the electric field. The increase of the luminosity intensity in the region of the gaseous nonhomogeneities with a lower density must be basically associated with the increase of the average electron energy resulting from the increase of its mean free path between collisions with the molecules and, therefore, must be proportional to the density variation. The disturbances introduced by the discharge into the stream must be small as a result of the very small amount of energy released in the gas.

The accuracy of setting the angle of attack in the tunnel with account for the sting deformations was of the order of $\pm 1.5^\circ$, the angles $\varphi = \pm 1.5^\circ$.

For the tests using the high voltage electric discharge, the models were fabricated from electrically insulated materials with a metal nose section. A conductor connected at one end with the model metal nose section and at the other end with the cathode of a high voltage rectifier was located inside the model (Fig. 3).

The needle-shaped anode in a plexiglas holder was located above the test region so that the lines of force of the electric field intersected the test region and its aerodynamic disturbances did not strike the model or distort the flowfield.

A ballistic resistor which limited the maximal current magnitude was installed in the high voltage circuit of the rectifier to ensure safe operation. The magnitude of the discharge current and voltage was selected to provide a stable luminosity pattern. To do this the reduced electric field intensity $E/p$ was selected so that the corresponding average energy of the electrons was approximately equal to the threshold value of the excitation function from 10 to 16 eV (Fig. 1).

As a result of the difference in the gas densities, resulting from the aerodynamic nonhomogeneities, the quantity $E/p$ will vary; for example, for the considered case $E/p = 10$ V/cm-mm Hg in the center of the vortex region and $E/p = 5$ V/cm-mm Hg in the supersonic region, and the average electron energies will differ correspondingly. Film used for aerial photography was used to photograph the luminous discharge. A thin layer of black oily liquid was applied to the model surface for flow visualization in the boundary layer.

Fig. 1. Observed nitrogen excitation functions in arbitrary units versus electron energy $E_e$ (in eV).

§2. Models and experimental technique. The experimental studies were conducted in the wind tunnel described in [9] at $M = 2$ and $R = 0.9 \times 10^6$, calculated for a length $l = 0.1$ m.

Three wings and three circular cones were used as the models. Two of the wings were triangular in planform with clipped tips and had leading edge sweep angles of $\chi = 82$ and $76^\circ$; the third wing had a cranked leading edge with $\chi = 76^\circ$ and $\chi = 56^\circ$. The wings had a symmetric profile with relative thickness $c = 5\%$. For mounting the wings to the sting each had a thickened section in the center in the form of a cone which transitioned into a cylindrical part. Figure 2 shows sketches of the wing models with $\chi = 76^\circ$ and $\chi = 76^\circ-56^\circ$ with the basic dimensions and cross sections. The $\chi = 82^\circ$ wing differs from the $\chi = 76^\circ$ wing only in aspect ratio. The cones had half angles of $\theta = 10^\circ$, $15^\circ$, and $20^\circ$ with cylindrical adapters used for mounting them to the sting.

The models were located in the flow core of the tunnel working section with the aid of curved stings, which were fabricated to mount the models at fixed angles of attack. The models were tested at angles of attack $\alpha \simeq 11.5^\circ$, $18^\circ$, and $25^\circ$.

A schematic of the model-installation in the tunnel is shown in Fig. 3. The sting could be rotated about its axis and the model could be observed in various projections (from a side view with $\varphi = 0$ to a top view with $\varphi = 90^\circ$).

§3. Test results. Figures 4-7 show photos of the flowfield near the wings and cones, obtained with the aid of the high voltage electric discharge method; for the wing with sweep angle $\chi = 78^\circ$ and the cone with half angle $\theta = 10^\circ$ the oil film and schlieren methods were also used for flow visualization. On the photos taken with the aid of the high voltage discharge technique we see clearly the vortex trails, which are the flow zones with lowest density. The vortices emanate from the