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VISUALIZATION OF THE THREE-DIMENSIONAL FLOW
AROUND A MODEL WITH THE AID OF A "LASER KNIFE"

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V.N. Kharchenko

Translation of "Vizualizatsiya prostranstvennogo
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16. Abstract The present work describes a method for visualizing the three-dimensional flow around models of various shapes in a wind tunnel at a Mach number of 5. A laser provides a planar light flux such that any plane through the model can be selectively illuminated. The shape of shock waves and separation regions is then determined by the intensity of light scattered by soot particles in the flow.					
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Visualization of the Three-Dimensional Flow
Around a Model with the Aid of a "Laser Knife"

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The article describes the layout and findings of experiments to visualize the three-dimensional flow around models of various shapes in a wind tunnel at $M_0 = 5$. An optical system is used to form a planar light flux (laser knife) that can be positioned in any given section about the model. The intensity of light scattered by soot particles in the flow is used to determine the shape of shock waves and the regions of detachment.

Visualization of the flow around models helps explain the structure of the flow and sometimes enables an analysis. To visualize the flow of gas at the surface of a solid the methods of silk thread, oil film [1] and washout points (cf., e.g., [2]) are used. These and other similar methods will determine the regions of detachment and their boundaries on the surface of the solid. Thermal indication dyes can also visualize the flow of gas at the surface of a solid [2]. The straight shadow method, the Tepler method and the interference method can visualize the structure of the agitated flow of gas both at the surface of a solid and at a distance from it. In order to use these methods at low (subsonic) velocities, it is necessary to mix a foreign gas to the main gas [3,4] or to perform a local

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* Numbers in margin indicate pagination of original.

gas heating [5]. At supersonic velocities these methods can visualize shock waves. It is often possible to observe detachment and other flow phenomena as well. Shadow methods are extremely effective in investigating planar and axisymmetrical flow and have become very popular.

But for three-dimensional flow, shadow methods can only observe the flow structure in a single longitudinal section, and only when the solid is relatively simple in shape. Additional information can be gathered by turning the model relative to the axis of the wind tunnel. For the visualization of conical three-dimensional streams, a shadow instrument is used successfully, with its light source placed at the vertex of the conical flow ("conical" shadow instrument [6]).

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The method of a spherical screen is used to visualize arbitrary three-dimensional streams [1,7]. The flow of gas is made visible by adding water or by cooling the gas below its condensation temperature while expanding. This method was used for interesting observations of three-dimensional gas flows, e.g., above the upper surface of a triangular airfoil [8,9]. However the condensation of gas or water vapor may be accompanied by discontinuity of condensation and distortion of the temperature field. Furthermore, the visualization of the flow takes place at stream parameters (Reynolds number, temperature factor) that differ considerably from those usual to other investigations (measuring heat exchange, pressure distribution, aerodynamic force). An electron beam is successful in visualizing low-density gas flows [10,11].

In the work described here, light scattering by dust-laden air is used to visualize the stream.

The dust content of the air can be either natural or artificially created by introducing dust into the forechamber of the wind tunnel. A convenient light source is the laser. This allows



considerable increase of the luminous power and simplifies the optical layout of the instrument.

1. The experiment was done in a supersonic wind tunnel at $M_\infty = 5$, stagnation pressure $p_0 = 8 \cdot 10^5$ Pa, and stagnation temperature $T_0 = 500$ K. The active portion of the tube was in the form of an Eifel chamber 0.8 m in diameter, within which there was a stream of gas 280 mm in diameter. The flow in the tube was heated by a kerosene heater, and therefore a certain amount of soot was present in the gas. Estimates showed that the soot particles had a size of 0.5-1 μm ; their concentration was $\sim 10^6$ cm^{-3} . The possibility of using a laser as the light source was evaluated in accordance with such characteristics of the dust content of the flow.

The experiments used two light sources: primarily the LG-75 He-Ne gas laser with continuous emission in the red spectrum ($\lambda = 6328$ Å and a power of 25 mW; and in some cases the LGI-37 pulsed gas laser, which generates several wavelengths and has its maximum energy in the green spectrum. The largest emitted power in the pulse was 2 kW, length of the pulse was 0.3 μs . In the experiments, the pulsed laser emitted a series of pulses with frequency 100-700 Hz.

Fig. 1 shows a layout of the "laser knife". Light from the laser 1 passes through an optical system 2, designed to shape a planar light knife 5. This system is a combination of a short-focus cylindrical and a long-focus spherical lens. Because of slight divergency of the light beam, the thickness of the laser knife varies along the length, but on the average is 2 mm. Scanning of the knife was achieved by a pivoting prism with total internal reflection 3, secured to the optical bench. The lens could be moved in the horizontal direction and positioned at various angles, allowing the laser knife to be oriented in any given section about the model 7. The position of the knife was calibrated on the scales 4 of the optical bench. The field of flow in the plane of the light

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knife was photographed through a window in the wall of the active section of the AFU chamber 6 on aerial film (isopanochrome, type 15-1000). The exposure time was 1-10 s.

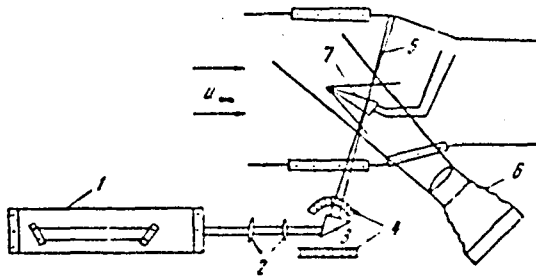


Fig 1

The visualization by this method is based on the change in intensity of the light scattered by particles in the various regions of the field of flow. In regions of elevated density the number of particles should increase and, consequently, so should the intensity of the light scattered by them. Thus, e.g., it is possible to determine the position of shock waves. In regions of flow detachment the number of particles should diminish; these areas will be dark on the photographs. The capabilities of the method were verified in a series of tests.

2. In [2] the flow of gas and heat exchange at sharp and blunt half-cones were investigated. The readings, taken by thermal indication coatings, revealed that narrow lengthwise zones of intense heat exchange are formed at the flat surface of the half-cone at angles of attack $\alpha \geq 0$. Visualization of gas flow at the surface of the half-cone by using a dye stream indicated that this process involves detachment of the boundary layer at the lateral edges of the half-cone and an attachment near the plane of symmetry. However the shadow methods (straight shadow method and Tepler method) were not able to observe the detachment zone.

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Study of the flow by means of the laser knife totally confirms the formation of detachment zones near the planar surface of the half-cone when $\alpha \geq 0$ whether the cone is sharp or blunt. Fig. 2 shows photographs obtained by the laser LG-75 with $\alpha = 10^\circ$ on a half-cone with half-angle $\theta = 15^\circ$ at the vertex. The photograph reveals a shock wave 1, induced by the conical surface of the model, and a detachment zone 2. The gas compressed in the shock wave shines¹ more intensely than that in the undisturbed flow. The glow of the gas behind the shock wave decreases in proportion to the distance along it from the lateral edges to the plane of symmetry in accordance with the declining intensity of the wave. In the detachment zones there is practically no glow, which in fact allows clear visualization of these zones. The lack of a glow in the detachment zones is apparently explained by two factors: 1) the reduced influx of particles into the detachment zone during three-dimensional flow and the absence of an influx during two-dimensional flow (in the latter case the detachment zone is closed on itself); 2) separation of particles due to vortical motion of gas in the detachment zone.

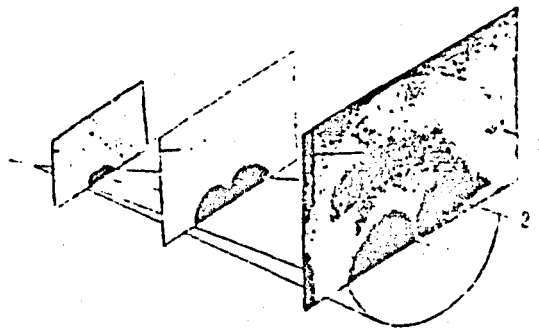


Fig. 2

The laser knife can determine the shape of the shock wave and the detachment zone. After processing of the photographs, some

¹Here and afterwards we envision a shining of the gas through light scattering by soot particles as opposed to the self-luminescence of gas at high temperatures.

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quantitative data was obtained. The shock wave at the flat surface has conical shape when $\alpha = 0$ and 10° . The maximum height of the detachment zone also varies by linear law along the length of the half-cone, except for the vicinity of the cone vertex. When $\alpha = 0$, the maximum height of the detachment zone at the bottom profile of the model ($x = 120$ mm) was 5 mm; when $\alpha = 10^\circ$, 15 mm.

3. The laser knife was used to visualize the flow near a triangular airfoil with 70° sweep.

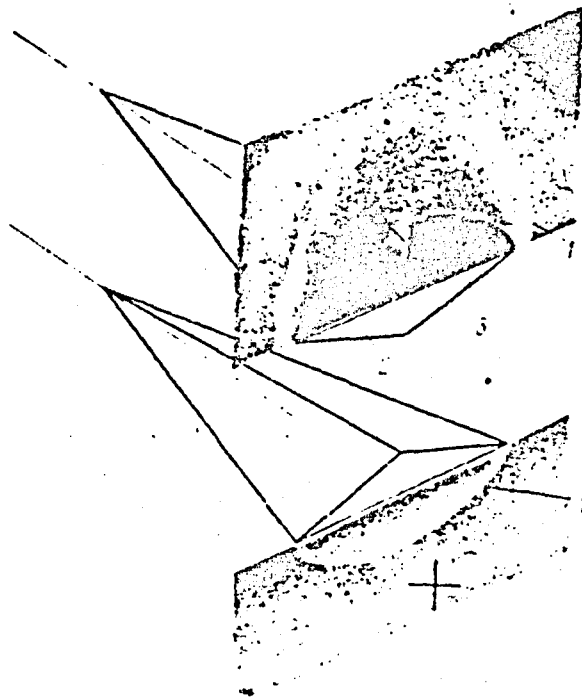


Fig. 3

Fig. 3 shows photographs made at angle of attack $\alpha = 15^\circ$ in a cross section situated at a distance of 10 mm from the rear edge of the model (overall length of model 150 mm). The LGI-37 laser was

used. A montage of two photographs is shown, obtained in different runs. In both runs the laser knife was oriented vertical above the planar surface of the model, which was positioned at angles of attack $\alpha = +15^\circ$ and -15° ; consequently, the plane of the laser knife was inclined at an angle of 75° to the leeward surface and an angle of 105° to the windward surface. Furthermore, the finite thickness of the model should be considered; the transverse section of the model had a triangular shape, the upper surface was flat and the lateral edges were sharp. The photograph shows a somewhat distorted flow pattern; in particular, the lower and upper portions of the shock wave do not coincide at the lateral edges.

The photograph distinctly reveals the flow pattern. A shock wave 1 is visible below and above the wing. Also, above the wing there are two distinct zones of detachment 2; the asymmetry of the detachment zones is due to inaccuracy in positioning of the model in the tunnel. The flow detached at the lateral edges is rejoined along the line of symmetry of the wing. This line, as shown by previous investigations [9,12], is the line of spreading, where local increase in the heat exchange ratio occurs.

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The photograph reveals a substantial increase in gas luminosity above the detachment zones near the plane of symmetry, indicating compaction of gas in this region. The boundaries 3 of this region apparently correspond to suspended shock waves. A shock wave 4 can also be seen issuing from the nozzle. The model and all the flow disturbances associated with it are situated inside the cone formed by this wave.

By comparing the photographs shown in Fig. 2 and 3 we may infer that the laser LGI-37 provides more distinct photographs than the laser LG-75. This is due to the higher luminous power of the former, as well as the fact that the photographic film is more sensitive to the green than the red spectrum.

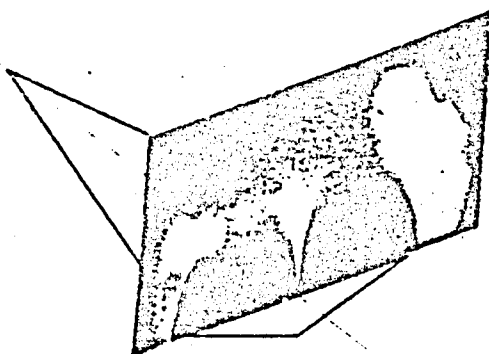


Fig. 4

Tests were conducted to visualize the flow pattern in the absence of soot particles: with the kerosene heater turned off, condensation of air began in the cold flow and light-scattering particles appeared. Fig. 4 shows a photograph obtained at the leeward surface when $\alpha = 15^\circ$. It is evident that the basic flow pattern (shape of the shock waves and detachment regions) is virtually the same as that of Fig. 3, although the dimensions of the detachment regions are heavily increased by the air condensation. /47

Fig. 5 shows the results of a photometry of the photographs, allowing for scale and photography angle. At the left is the result of photometry of the photograph with soot particles present (cf. Fig. 3), at the right the result under identical conditions with condensation of air (the numbers are the same as in Fig. 3). It is obvious that the dimensions of the detachment region increase upon condensation of air, and their shape is also somewhat changed.

4. A third example illustrating the capabilities of the laser knife is the testing of a cone with a jet blown into the stream. /48

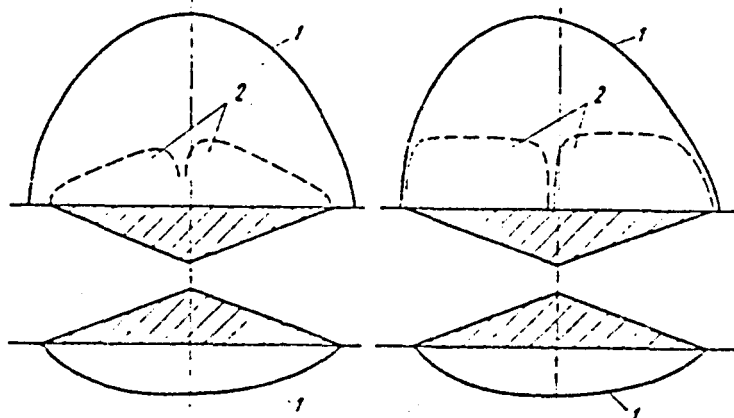


Fig. 5

The model is in the form of an acute cone with half-angle $\theta = 5^\circ$ at the vertex. A second jet of air was injected through a conical nozzle with $M_j = 3$. The diameter of the outlet section of the nozzle was $d_j = 6$ mm.

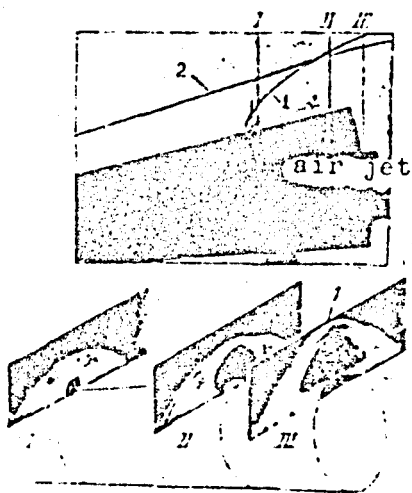


Fig. 6

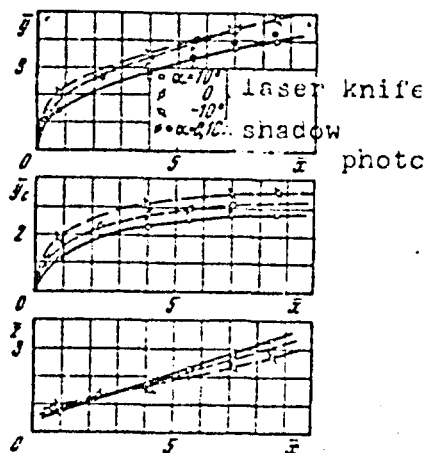


Fig. 7

Fig. 6 shows photographs of the flow, obtained by laser knife (laser LG-75) at $\alpha = -10^\circ$ and absolute pressure of injected air $p_{0j} = 4.25 \cdot 10^5$ Pa (the nozzle was located at the windward surface). This same figure at the top shows a shadow image obtained under the

same conditions. The photographs taken with laser knife clearly reveal the second stream, since the injected air carried no dust and therefore did not glow.

The layer of air compressed in the shock wave 1 induced by the jet and enclosed between this wave and the boundary of the jet is quite visible. Also visible on the photographs is the shock wave 2 induced by the surface of the cone. At a certain distance downstream from the injection site, waves 1 and 2 intersect.

We observe that the straight shadow method cannot determine the boundaries of the jet. The laser knife method can also be used to study the flow in the jet itself. For this, dust must be mixed into the injected gas.

Fig. 7 shows the results of measurement of waves 1 and 2, as well as the contour of the jet at $p_{0j} = 2.8 \cdot 10^5$ Pa and various angles of attack. The information on the vertical recession of the wave $\bar{y} = y/d_j$ obtained by the shadow method practically coincides with that by the laser knife. The other dimensions shown in Fig. 7 were obtained exclusively with the laser knife (all the dimensions are referred to the diameter of the outlet section of the nozzle.) The cross section of the jet has an irregular shape. This can be inferred from the shape of the shock wave induced by the jet: The distance from the line of symmetry to the shock wave along the vertical \bar{y} is much larger than that along the horizontal \bar{z} . At $\alpha = -10^\circ$ the cross sections of the jet are more vertically prolate than when $\alpha \geq 0$. At a certain distance from the nozzle, the upper limit of the jet y_c is deflected toward the surface of the cone.

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Thus, the photographs by the laser knife supplement the findings of other visualization techniques and enable a better understanding of the pattern of complicated three-dimensional flow around solids.

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