M.P. GOLUBEV

Seeing the invisible

Air practically neither absorbs nor reflects light in the visible spectrum; it does not emit its own beams either. Nevertheless, based on this invisible substance, we can move on special winged vehicles (airplanes) with velocities greater than the pedestrian velocity by a factor of many hundreds! How is it possible to make a flight most effective and, at the same time, as safe as possible? The answer to this question is obvious: it is necessary to study specific features of air flows around the flying vehicle. Therefore, one of the urgent problems of aerodynamics posed more than a century ago and becoming even more urgent with increasing aircraft velocities is to "see" these powerful, but still invisible air flows

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After the success achieved in aircraft technologies in the last century, it may seem surprising that the efforts currently applied to improve the flying vehicle shape practically do not contribute to further improvement of flight properties. This is evidenced by the similarity of the outward appearance of airplanes of the same class, which were developed by various aeronautical designers for the last years.

This is not surprising: the laws of aerodynamics are identical for everybody; therefore, all designers independently find the most effective shape of the *airframe* (airplane body) with required flight performance. Comparing, for instance, modern fighters of the fifth generation (American F-22 Raptor and T-50, being developed in Russia), one can easily notice the similarity of their contours, shapes of the wings and tail fins, close angles of inclination of the fins, etc.

It should be admitted that the limit of the airframe fabrication technology based on the Zhukovsky's theory has actually been reached. This fact, however, does not restrict further development of aeronautics. At the moment, the aircraft performance is improved by means of flow control around the flying vehicle.

It is known that aircraft motion in an air flow may involve adverse phenomena increasing the drag force; these are primarily the formation of vortices and shock waves, and also flow separation from the body surface. It is important to study these aerodynamic phenomena because designers want to make the airplane more cost-efficient and to increase its flight velocity. Controlling the emergence and evolution of these processes can improve vehicle controllability, reduce fuel consumption, decrease visual and acoustic perceptibility of the vehicle, extend the range of available flight regimes, etc.

At the stage of aircraft design, much attention is paid not only to the experimental, but also to the numerical studies of the flow around the airframe and various structural elements of flying vehicles (external elements of the engine, inlets, doors, and attached equipment). Development of more powerful computers has made it possible to improve the mathematical calculations of air motion parameters.

Nevertheless, the complexity and variety of aerodynamic phenomena often restrict the possibility of numerical simulations of real flight conditions; for this reason, computations are either insufficiently accurate or cannot be performed at all. In such situations, the only way out is to perform experimental studies, which provide both quantitative information and a clear idea about the overall pattern of the process.

Aeronautic designers in a tunnel

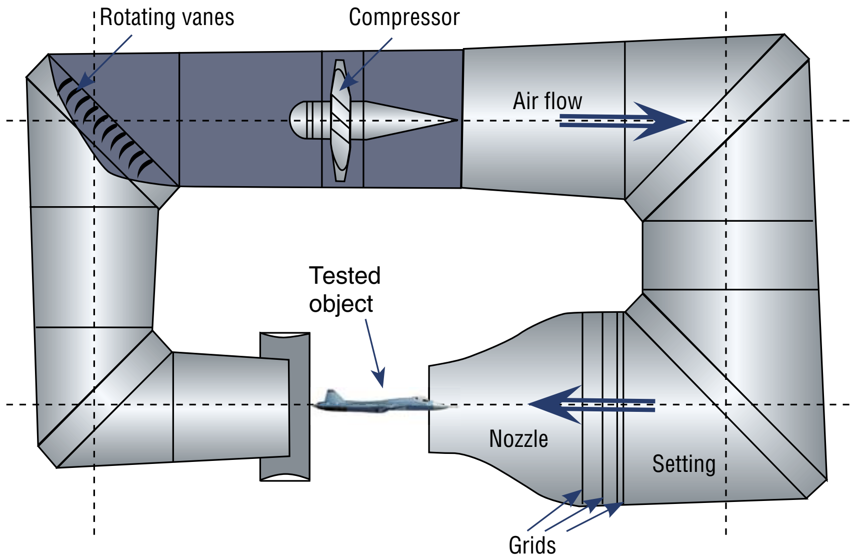
From the viewpoint of a pilot (and of a vehicle) in flight, it is not important whether the vehicle moves in a quiescent air medium or an air flow is incoming onto a "hanging" airplane. Therefore, there are two types of experiments: either objects to be examined are placed into an air flow in the so-called *wind tunnel* or these objects are attached to an aircraft and tested in real flight conditions. Various sensors are used to measure the pressure and temperature, the lift and drag forces, loads, etc.

Generally speaking, in-flight data are more reliable, but these experiments are rather expensive and often nonpractical.

To study the flow around a full-scale model or a real aircraft, one needs a wind tunnel of a tremendous size. Such a wind tunnel is available for researchers, for instance, at the NASA AMES research center. It can accommodate a full-scale Boeing-737 airplane. There are only few facilities of this kind in the world, and they mostly operate at comparatively low velocities (below 200 km/h), mainly modeling problematic low-velocity flight modes (e.g., landing).

Most investigations are performed in smaller-size wind tunnels. In this case, the experiment can be made less expensive, and the range of flow parameters can be extended. Either a small-scale model of the entire vehicle or various full-scale or small-scale elements of the vehicle are tested in such tunnels. Objects to be tested are not only airplanes, but also cars, trains, buildings, etc. Simple geometric shapes (sphere, cylinder, flat wedge, or cone) are sometimes used to study the basic effects and phenomena.

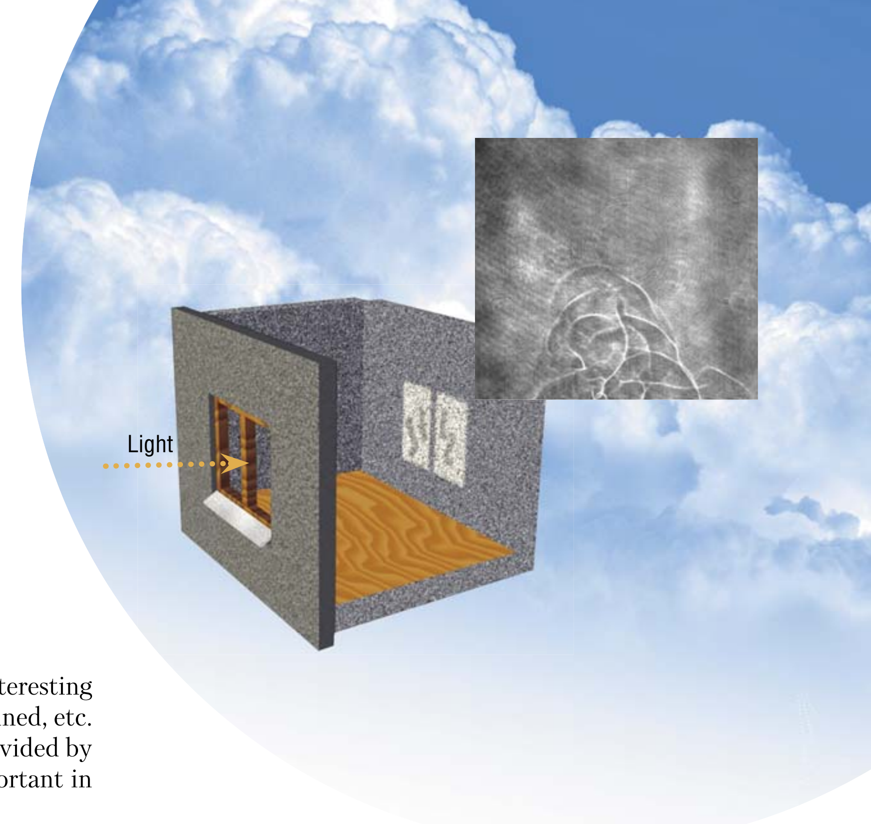
Nevertheless, it is often insufficient to perform an experiment and obtain a set of numbers (values of temperature and pressure, values and directions of air flow velocity at various points). The visual image complementing the "numerical" image of the process sometimes provides even more valuable information, because it allows some specific



A wind tunnel is a device designed for testing flying vehicles. There are various types of wind tunnels, but the general principle is identical for all of them: an artificially generated air flow passes around the tested object, modeling the flight of the latter. The main element of the wind tunnel (compressor) pumps the air into the settling chamber (the wide part of the tunnel), where the air flow is decelerated and passes through a set of grids eliminating inhomogeneities of the velocity field. After that, the air flow enters a constricting nozzle, wherefrom it passes with acceleration to an open test section (where the measurements are performed). If it is a closed-type wind tunnel, the air flow is then directed back to the compressor. The corner joints of the wind tunnel are equipped with special rotating vanes, which smoothly change the flow direction and do not allow additional turbulent vortices to develop in the flow

The greatest wind tunnel in the world is located in a set of hangars of the NASA AMES research center (California, USA). It is 25 meters high and 50 meters wide; it can accommodate a 180-seat airbus. The compressor system of blowers is fed by a 100-MW electric power station located nearby. Flying vehicles to be tested are attached on vertical struts. Changing the relative heights of these struts, it is possible to align the vehicle at needed angles to the flow direction

On a bright sunny day, one can see a shadow pattern on the wall opposite the window: an interesting phenomenon initiated by inhomogeneities of heated air



features of the air flow to be identified, the most interesting areas for subsequent investigations to be determined, etc. A helpful tool for researchers in this aspect is provided by *optical* diagnostic methods, which are quite important in aerodynamic studies.

Shadow of an invisible man

The essence of optical methods in aerodynamic research is determining air flow parameters via changes in properties (e.g., intensity, frequency and phase of oscillations) of radiation transmitted through this medium. Using physical principles forming the basis of this or that method, one can determine the gradients of pressure and gas density, flow velocity, etc.

Optical methods offer two undoubted advantages: they are *contactless* (nonintrusive) and *panoramic*. In other words, they do not affect the "object-air" system under study and often allow obtaining data in the form of an image in the entire flow field.

Among various optical methods, we should mention flow *visualization*, which is not less important than measuring flow parameters, because visualization provides a clear general pattern of the flow.

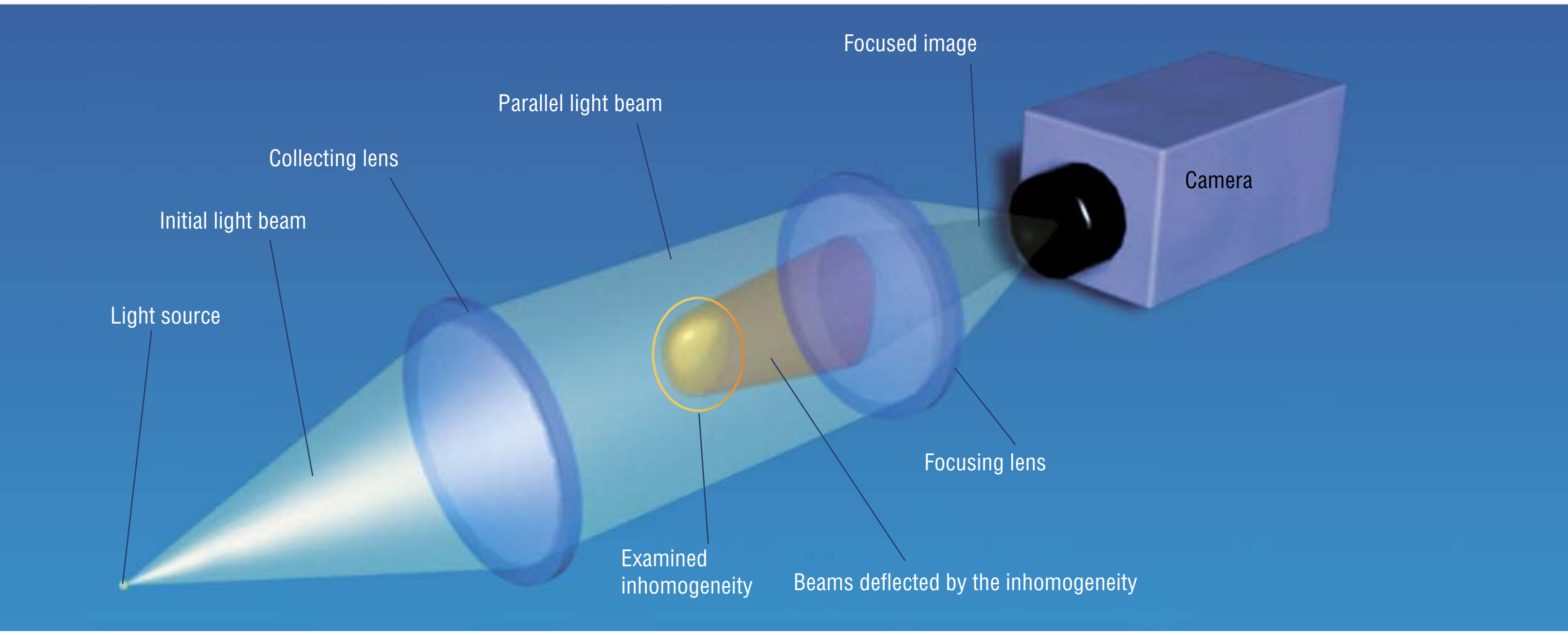
Being very simple, the first method of visualization that became popular was the so-called *shadowgraphy*. It can be illustrated in a simple way: on the wall illuminated by the direct sunlight coming through the window, one can see air inhomogeneities in the form of dark and light spots. The reason for this phenomenon is the lower density and, hence, the lower refractive index of the air heated near the warm wall. Owing to the difference in these parameters with the ambient air, the sunbeams are deflected by moderate angles; the luminosity increases at some places on the wall and decreases at other places (i.e., something like shadows of inhomogeneities is observed).

Certainly, sunlight is not used in aerodynamic experiments. Instead, artificial sources of light are used: incandescent lamps, light-emitting diodes, spark dischargers, etc. The essence remains the same: the shadow of medium perturbations induced by its interaction with the object is seen on the screen. This method is called the *shadowgraphy*.

If the image should be reduced to the size of the input lens of the camera, then a collecting lens is placed between the examined region and the screen. In photographs obtained by this method, one can see, for instance, the location and shape of shock waves and turbulence in the boundary layer of the flow along some obstacle. As the difference in density across the shock wave is very large, they look as dark lines because they ensure rather strong deflections of radiation. In subsonic flows with sufficiently high (transonic) velocities of the flow, the differences in density are not that large, but the beam can be deflected rather significantly if there is a large-size inhomogeneity aligned along the beam, and the corresponding shadow pattern will be formed.

The greater the difference in density, the greater the difference in brightness on the shadow pattern. If inhomogeneities are weak, however, the intensity of the deflected beams can be so small that they will not be visible on the background of overall illumination. To overcome this difficulty, it is necessary to cut off the background radiation.

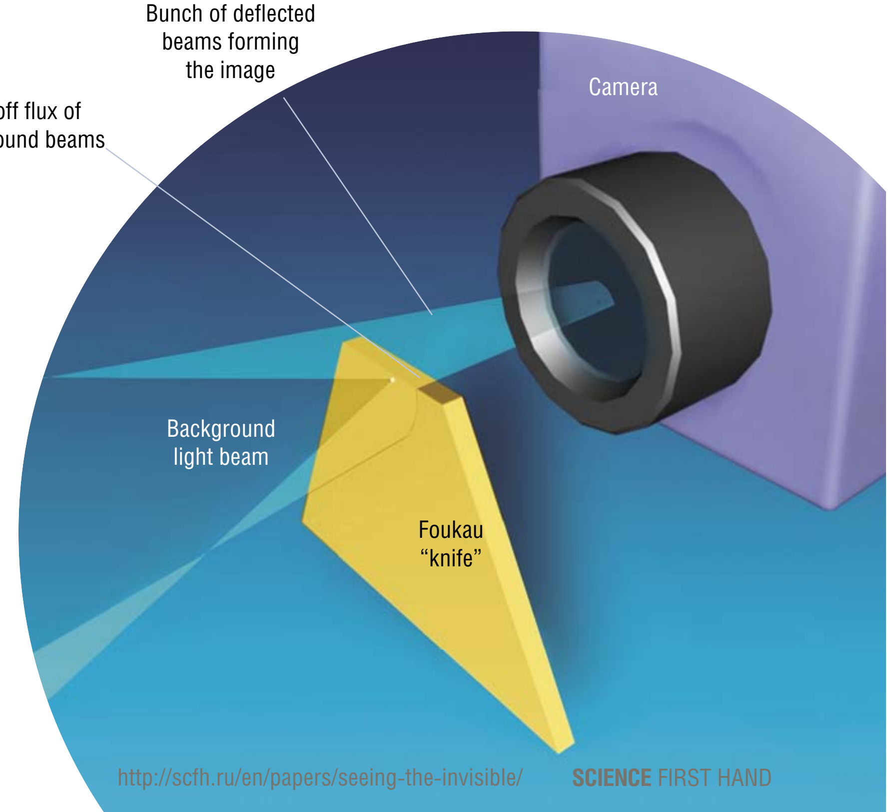
A method to cut off extra light was proposed back in 1857 by the French physicist Foucault. To monitor the accuracy of mirror fabrication, he decided to place a non-transparent screen with a sharp edge into the focal plane of the mirror. Seven years later, his method was improved by the German physicist Toepler. He proposed to use a scheme with a screen cutting off the background radiation (Foucault knife) to search for inclusions of foreign particles (including air bubbles) in various articles made of glass, in particular,

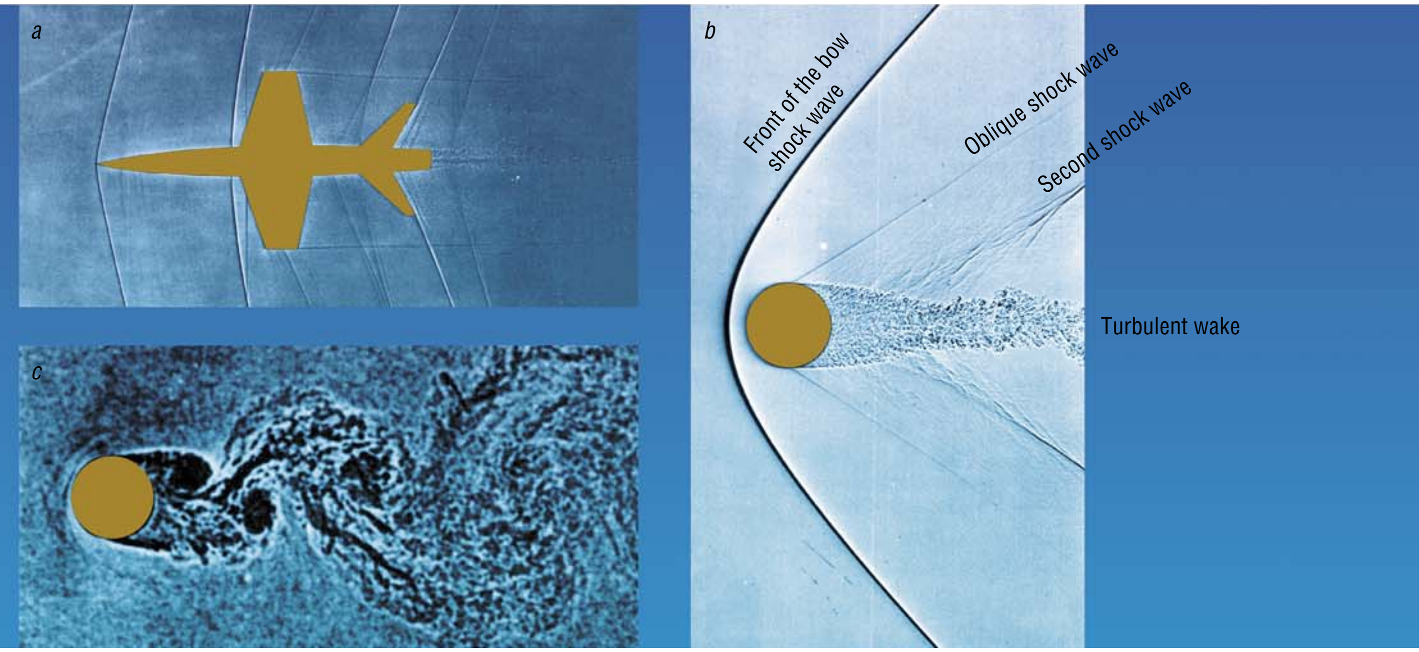


Shadow methods of visualization are based on the phenomenon of shadowing by local perturbations in air. A shadow pattern appears because light beams passing through locally condensed or rarefied areas of the gas are deflected from a straight path

The essence of *shadowgraphy* involves generation of a parallel light beam with the use of a light source and a collecting lens; this light beam is transmitted through the examined area of the air medium. If there is an inhomogeneity, the set of deflected beams forms an image, which is focused by the second lens onto a screen or camera.
In the case of weak perturbations of air density, however, the shadow pattern has a low contrast, and it is difficult to distinguish the details of the image

"Schlieren photography" is a shadow-based method providing images with a higher contrast. For this purpose, a non-transparent plate or a disk is placed in the area where the background radiation is focused; the latter is cut off by this "knife." Light beams deflected by the examined inhomogeneity, however, pass predominantly outside the focal point; therefore, the majority of these beams do not cross the "knife" and fall onto the camera. Thus, the ratio of intensities of the deflected and background radiation is substantially increased, and the inhomogeneities are more clearly seen as light areas on the dark background





Supersonic flight is inevitably accompanied by the formation of shock waves with large differences in density, which are seen in schlieren pictures as high-contrast lines.
For instance, shock waves are generated by protruding elements of the aircraft model "flying" with a supersonic velocity of 420 m/s (*a*). In a supersonic flow around a sphere (*b*), one can clearly see the front of the bow shock wave (having a hyperbolic shape), with oblique (plane) shock waves emanating from the top and bottom points of the sphere. Immediately behind the sphere, there is a turbulent wake generating weak perturbations, which later merge into the second shock wave. In a subsonic (with a velocity of about 210 m/s) flow around a cylinder (*c*), the wake is formed from vortices alternatively shed from the top and bottom points

to monitor the quality of lens manufacturing. Toepler called this method the *schlieren* method, from the German word «Schlieren» (defects, noise, or dirt in a transparent medium). A little bit later, this method was applied to gas media diagnostics.

Photographing air

In a schlieren picture of a supersonic jet obtained with a horizontal "knife," the images of the upper and lower halves have different brightness. This occurs because the beams forming the image are partly overlapped by the "knife." Therefore, instead of the plate, researchers often use a black point on a transparent glass with radiation directed toward the center of this point. As a result, it is possible to cut off only the background radiation focused at this point.

Other masking devices placed to the focal point can also be used. As the absorption of extra radiation by these elements provides a high-contrast image on the screen (i.e., an invisible object is visualized), these devices were called the *visualizing elements*.

maller the size of the "point" of focused background
ɔn and the size of the element absorbing this ra-
, the greater the sensitivity of the optical scheme.
ɔre, the use of lasers in schlieren methods could be
:ular interest, because laser radiation can be focused
arrow beam several micrometers in diameter (hun-
f times thinner than a human hair).
ılity, however, it is next to impossible to direct a
beam exactly to an edge or to an extremely small
nall oscillations (vibrations) of the schlieren device
ort its orientation, and edge roughness, commensu-
size with focused radiation, will introduce strong
ons into the visualization pattern. For this reason,
of lasers has not resulted in a significant increase
tivity.
, it has been assumed until recently that there is
for shadowgraphy visualization: the difference in
should be greater than 10^3 kg/m^3 (this is approxi-
one thousandth of the surface-layer atmospheric
ity). Nevertheless, this is insufficient for studying
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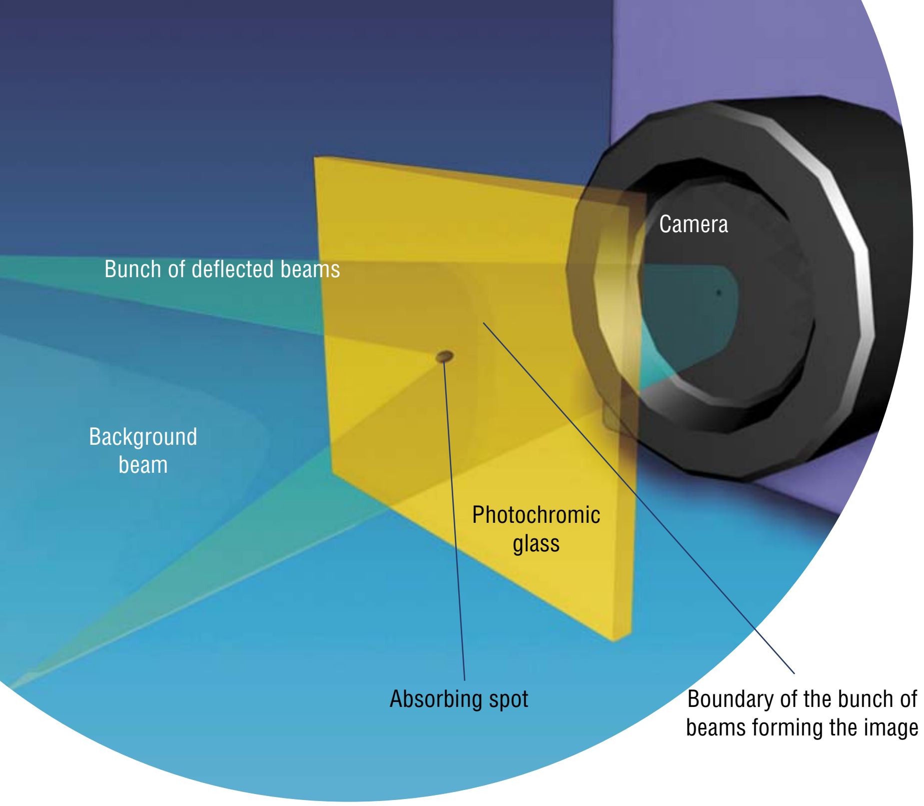
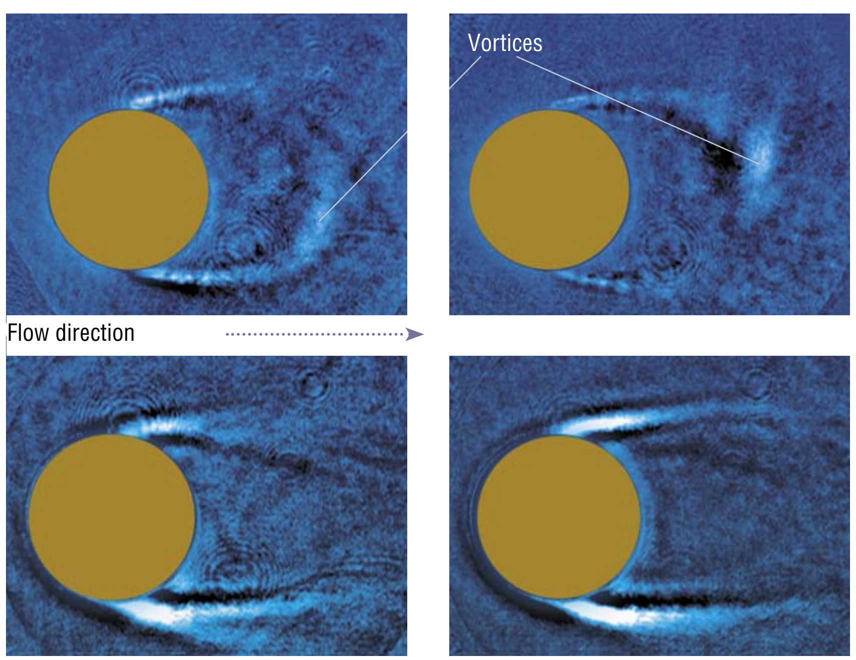


An effective modification of the schlieren method has been recently developed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian branch of the Russian Academy of Sciences (ITAM SB RAS). “Adaptive visualization transparencies” (AVTs) made on the basis of photochromic glass were used to cut off interfering radiation. This device offers a pioneering possibility of seeing extremely small perturbations in the gas (smaller than one thousandth of the medium density)

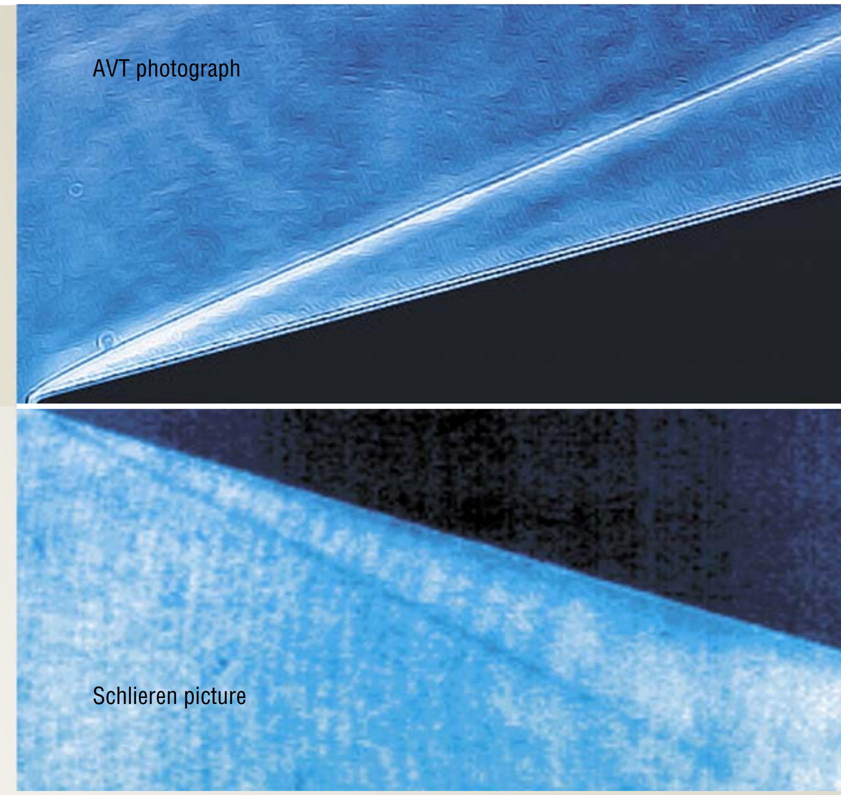
gas flows.

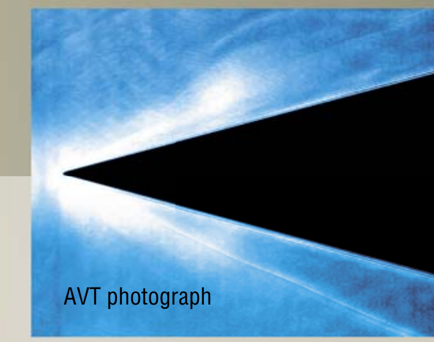
The sensitivity of the method was cardinally improved in 2006, when researchers of the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (ITAM SB RAS, Novosibirsk) proposed to use *photochromic glass* darkened by intense light instead of the “Foucault knife” (Pavlov et al., 2007). In everyday life, such materials are widely used for the so-called chameleon glasses, which become less transparent in bright sunlight, thus, protecting the human eyes.

The method of cutting off extra light with the use of a photochromic plate is quite elegant because the background radiation, focusing in the depth of the plate, generates a spot absorbing this radiation at a needed place and of an appropriate (minimum possible) size. Therefore, there is no need in precise tuning of such a shadow device, because, when the latter is shifted somewhere, the absorption spot is automatically generated at a new place, while the old spot disappears. The beams deflected on the inhomogeneity do not focus on the plate; therefore, they have extremely low intensity, do not generate an absorbing spot, and pass to the detecting camera (onto the screen).



Application of the AVT technology allows real-time observations of the formation of the vortex wake behind the cylinder (at a velocity of 10 m/s) and the formation of symmetric “moustaches” without vortices (1 m/s). These phenomena could not be visualized by other panoramic methods





The compression line (shock wave front) in a rarefied flow (about 10^{-3} atm) around a wedge can be only guessed in the schlieren picture, whereas it is clearly visible in the AVT photograph. Moreover, the AVT technology has allowed us to see how the shock wave is destroyed by an electric discharge

Wedge: one of the most popular aerodynamic models

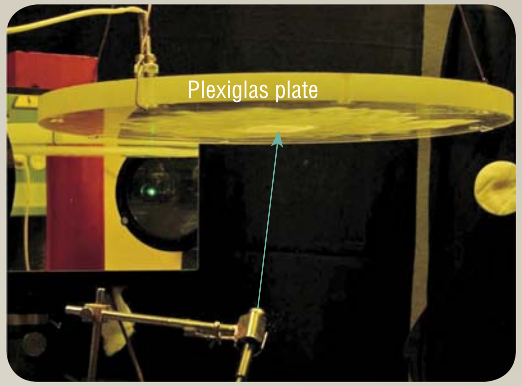
Owing to their ability to adapt to violations of instrument tuning, these visualization elements were called the *adaptive visualization transparencies* (AVTs).

This modification of shadowgraphy produced impressive results: now it is possible to observe flow patterns in extremely rarefied gases (with pressures below 100 Pa = 0.001 atm) and flows with extremely low velocities (below 1 m/s). The area of applicability of new visualization systems, however, is not restricted to these two cases.

Thus, a significant drawback of the classical schlieren method is the lack of the possibility of visualizing weak perturbations on the background of strong disturbances, because the latter make the image noisy as a whole. This is not a problem in using AVTs because the beams deflected on strong disturbances generate their own absorbing spots on the photochromic glass, independent of the main (background) spot. This effect attenuates the contrast of the image of drastic changes in air density, and details of weak perturbations can be seen.

The unique capabilities of the new method are also demonstrated by the example of studying processes that occur during absorption of a powerful bunch of infrared beams in a thin layer of an organic material. It was only with the use of AVTs that it became possible to observe details of phenomena inherent in the formation of a combustible gas mixture and its subsequent ignition: shock waves and the flow structure behind the shock waves, acoustic waves from ignited dust particles, and vortex flows in the plume.

It is impossible to obtain a detailed picture of a very bright object with the use of shadowgraphy or schlieren technique because of the extremely low sensitivity of the first method and extremely high sensitivity of the second one. Nonlinearity of light absorption by photochromic AVTs offers an excellent possibility of studying various processes without replacement of visualizing elements and without adjustment of the optical scheme.

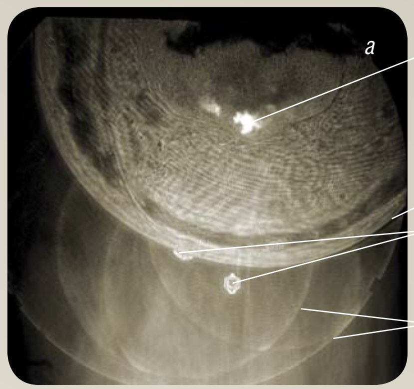


IR radiation is directed to the center of the plate from below. It rapidly heats a thin layer of the plate and air near the plate surface. Plexiglas evaporates, and rapidly expanding air generates a shock wave propagating away from the plate

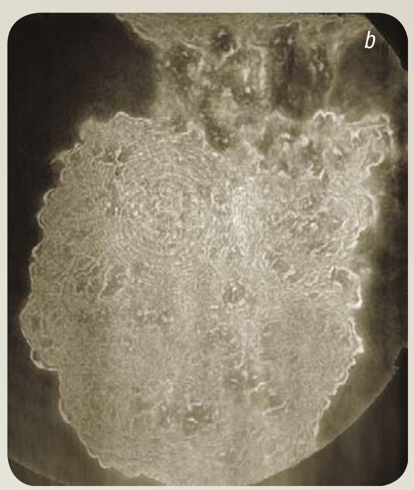
The unique capabilities of the new optical method are demonstrated in the experiment on evaporation and subsequent ignition of plexiglas under the action of a powerful flux of infrared beams.

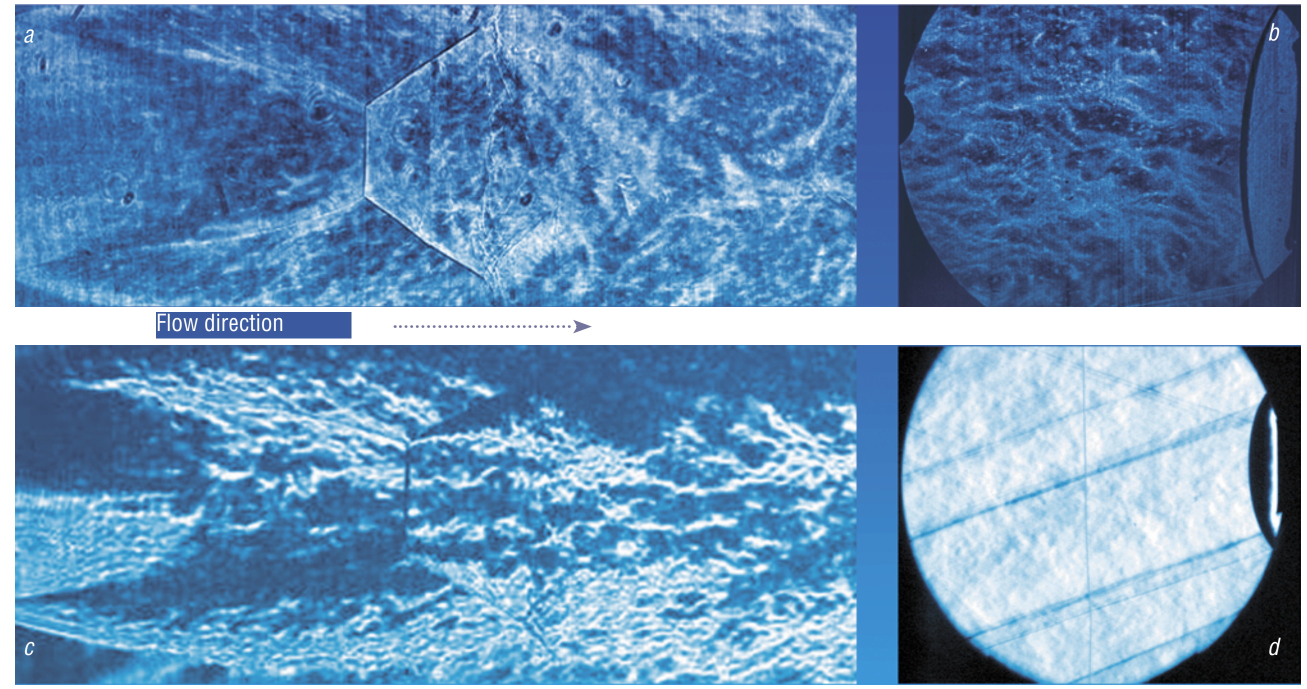
The AVT photographs (*bottom right* picture) show the explosive burning of dust particles (*a*) and the flow structure inside the plume (*b*)

Plexiglas vapors mix with strongly heated air, forming an explosive mixture, which rapidly ignites



The moving front of plexiglas vapors forms a burning plume





One of the principal advantages of AVT photography is the possibility of visualizing weak perturbations of air density on the background of strong disturbances. For instance, the system and contours of shock waves are clearly seen inside a supersonic free air jet (*a*), and almost the entire flow regime behind the shock wave can be observed in much detail in a supersonic flow around the flat face of a cylinder (*b*). At the same time, if the conventional method with the "Foucault knife" is used, the image becomes too noisy (*c*) or too dull (*d*)

Photochromic materials have been known for a long time, but only recently researchers have found a new application for them in optical diagnostics of gas flows. This elegant and essentially simple technical solution found by the researchers of ITAM SB RAS (Novosibirsk) has allowed some complicated problems of visualization techniques to be resolved.

Invention of a visualization system capable of adaptation has substantially extended the experimentalists' potential, and unique results of worldwide significance were obtained already at the initial stage of the system development. Owing to that, the AVT method was included into the list of the main achievements of the Russian Academy of Sciences in 2007.

The story of the new method is not finished: it offers a powerful potential for further improvement of sensitivity and performance.

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