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AEROGASDYNAMIC INVESTIGATIONS AT THE INSTITUTE OF THEORETICAL AND APPLIED MECHANICS IN THE LAST DECADE

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Introduction. Aerodynamics is a scientific basis of the most important fields of modern engineering: energetics, aviation, astronautics, and, in recent years, new technologies such as plasma and cold gas-dynamic deposition, acoustic drying of materials, wind-assisted energy production, and many others.

The range of problems of aerodynamic investigations at the ITAM (Institute of Theoretical and Applied Mechanics) was due to the efforts of the prominent scientists and academicians S. A. Khristianovich, V. V. Struminskii, and N. N. Yanenko. Each of them made an invaluable contribution to the formation of ITAM scientific directions that are being extensively developed at present. The most outstanding achievements in the field of aerodynamics at the new stage of development are presented in this review.

1. Experimental Base and Measurement Methods. In the last decade, the ITAM experimental base was improved. The Institute's complex of wind tunnels [1] covers the ranges of Mach numbers (M) from 0.01 to 25 and Reynolds numbers (Re) from 10^4 to $5 \cdot 10^7$, which allows one to simulate flow conditions at altitudes from 15 to 90 km. Figure 1 shows the simulation range of parameters in the field of basic gas-dynamic similarity criteria (M and Re). Three-digit numbers that begin with 3 denote ITAM tunnels and the corresponding curvilinear tetragons characterize the ranges of parameters covered by these tunnels. All wind tunnels are equipped with modern automated measurement devices. An El'brus-1 K-2 three-level automation system based on Elektronika-60, SM-3, SM-4, and BESM-6 computers was substantially updated. At present, each experimental station is equipped with a PC-based measuring-computational complex, including analog and pneumatic switches, analog-to-digital converters, etc. For example, for in-line processing, storage, and mapping of large amounts of information, personal computers with CAMAC transcomputer crates-controllers are employed on a T-313 supersonic wind tunnel, thereby making it possible to process data in real time and also to increase substantially the effectiveness of some experiments. Multiple studies of the characteristics of the reference models in ITAM tunnels showed high accuracy of the measuring systems, and comparison with similar data obtained at the Central Aerohydrodynamic Institute (CAI), NASA, DLR, ONERA, and other centers points to a good convergence of the aerodynamic characteristics of the models of different classes.

Along with the development of conventional experimental techniques (measurements with Pitot tubes, hot-wire anemometers, thermocouples, etc.), new and little known but efficient quantitative and qualitative methods of research were developed and introduced into practice. Optical methods whose important merits are contactless and the possibility of obtaining a large amount of information in a very short period were of particular interest. In T-313 experiments, a laser-knife method allowing visualization of the flow structure was employed. Dedicated equipment was designed and fabricated for introduction of light-scattering particles into the flow, for the formation of a flat laser beam (laser knife) in the flow region under study, and also for recording of flow patterns. The effect of the introduced light-scattering particles on the flow parameters was studied, and recommendations concerning the flow rate of a substance required for flow visualization were given. The method is widely used in studies of complicated spatial flows.

At ITAM, an optical method of measuring skin friction, which compares favorably with the previously known ones, was developed [3, 4]. The method is simple in realization and allows one to determine friction on curved, arbitrarily oriented surfaces.

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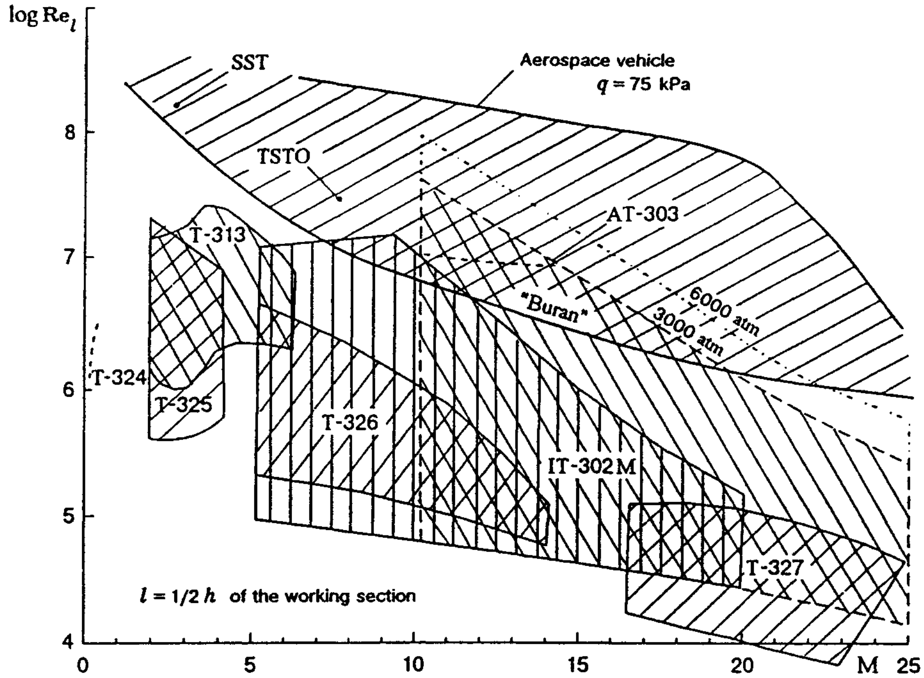

Fig. 1

Thin-film thermosensitive liquid-crystal coatings are widely used for visualization of temperature fields. The determination of an exact temperature value with the use of a color picture is a complicated technical problem. The temperature of a coating surface affects the light wavelength reflected from it, i.e., differently heated sections of the surface are differently colored. A so-called schlieren method which makes it possible to transform a color picture into a spatially band-modulated image in the form of an interferogram was developed [5–7]. The color and, consequently, the surface temperature depend on the magnitude of the shear of these bands. The method enables one to use black-and-white image receivers and simplifies substantially the acquisition of quantitative data.

The efficiency of optimal methods is largely determined by the possibility of recording and processing a large amount of information (video images). At ITAM, systems of image introduction directly into computer memory that allow one to record hundreds of frames in succession or according to a given algorithm were devised. A number of algorithms of data processing for the laser-knife methods, skin-friction measurement, and temperature-field recording with the use of liquid-crystal coatings and heat vision, etc. were elaborated [4, 6–10].

Studies of composites that combine the properties of liquid crystals and polymers necessary for temperature measurements on surfaces in flow were generalized in [11].

The creation of a new generation of transport systems capable of decreasing considerably the cost of transporting cargo and man to orbits of the Earth and other planets imposes new requirements for simulation of physical processes of the flight of flying vehicles with allowance for aerothermal effects in wind tunnels. In addition to the commonly accepted M- and Re-based simulation, it is necessary

— to reproduce the basic flow parameters using the pressure and temperature at $M \geqslant 10$;
— to take into account the period of flow about a flying-vehicle model;
— to ensure a high-purity working gas;
— to simulate the fields of acoustic and enthalpy disturbances;
— to simulate dissociation processes and nonequilibrium effects upon expansion in a nozzle;
— to reproduce the static temperature and the binary reaction parameter upon simulation of the initial stage of combustion in hypersonic ramjets and the triple reaction parameter at the final stages of and during

expansion of combustion products in nozzles [12].

All these requirements can be met simultaneously in none of the existing hypersonic wind tunnels or those being built in different countries of the world. These issues are being intensively discussed in the modern literature, and there are several practical ideas on the creation of such complex facilities. It is noteworthy that in solving concrete hypersonic flight problems, the flow parameters can be of different value, and, hence, it is possible to create channels simulating only some physical parameters.

At ITAM, the problem was posed to design a wind tunnel that would ensure the required purity of a working gas (air or nitrogen) in M- and Re-based simulation in a quasi-stationary mode of operation for 40–150 msec. For this purpose, use was made of the results of studies performed at the Lavrent'ev Institute of Hydrodynamics (LIH) and the Institute of Hydropulse Engineering (IHE) on the creation of high-pressure stands in plenum chambers. At present, an AT-303 adiabatic compression installation (see Fig. 1) is being built through joint efforts of the ITAM, LIH, and IHE (Siberian Division of the Russian Academy of Sciences), and the CAI based on the ITAM. This work is financially supported by the Presidium of the Siberian Division of the Russian Academy of Sciences. The implementation of this project is mainly due to Academician V. A. Koptyug. Upon completion, scientists will have obtained a unique instrument that offers the possibility of investigating promising aeronautic systems at natural Re and M values and at high degree of flow purity.

2. Hydrodynamic Stability and the Onset of Turbulence. Theoretical and experimental laminar–turbulent transition studies in subsonic and supersonic boundary layers and also in supersonic jets and shear layers were in progress.

Subsonic Flows. The weakly nonlinear theory of resonance interaction of Tollmien–Schlichting wave triplets in a laminar–turbulent transition in a boundary layer on a flat plate at small amplitudes of initial disturbances was evolved. Here the so-called subharmonic type of transition, which was discovered and comprehensively studied experimentally at ITAM for the first time [1],[1] was realized (this term appeared to be incorrect, and the term "N-transition" was suggested in [13]). Apart from the separation-out of a dominant subharmonic triplet, the parametric resonance was found to lead to energy transfer into a wide spectrum of low-frequency disturbances. Numerical results are in good quantitative agreement with experimental data and with the integration results of the full Navier–Stokes equations [14–18]. The effect of the pressure gradient on the resonance interaction of waves in triplets was analyzed in [19]. The wave interaction in the case of an essentially nonlinear primary wave was considered in [20].

Experimental studies of the process of laminar–turbulent boundary-layer transition on a flat plate were directed to a detailed consideration of the classical or so-called C-regime [1]. The experimental results led to a revision of the universal concepts of the onset of turbulence in this regime, in particular:

- Coherent structures of two types were discovered during their formation: structures connected with a strong three-dimensional shear (Λ-structures) and soliton-like structures [13, 21–25]. The latter show up as typical "spikes" on velocity pulsation oscillograms. Unlike the usual ideas, the mechanism of local inflectional high-frequency instability was shown not to play a significant role in the process of formation of these structures [23].
- It was found that the transformation of flow into a stochastic one begins in the near-wall region. Its mechanism is similar to that occurring in an N-regime. As was shown in [21, 22, 26], no breakdown of a strong-shear layer occurs at the stage of onset of this process.

Detailed quantitative information on the structure of a transitional boundary layer in this regime was reported in [27]. There is good quantitative agreement between the experimentally observed process of evolution of a transient C-regime and the results of direct numerical integration of the Navier–Stokes equations, as shown in [28]. The experiments dealing with the study of the last stages of a transitional N-regime and performed in [29] showed the processes of disturbance development to be similar to those occurring in a C-regime.

Comparative investigations of the laminar–turbulent transition in flow about a glider's wing in flight

[1]The subharmonic resonance is likely to be a universal mechanism of wave interaction in the process of onset of turbulence in shear flows.

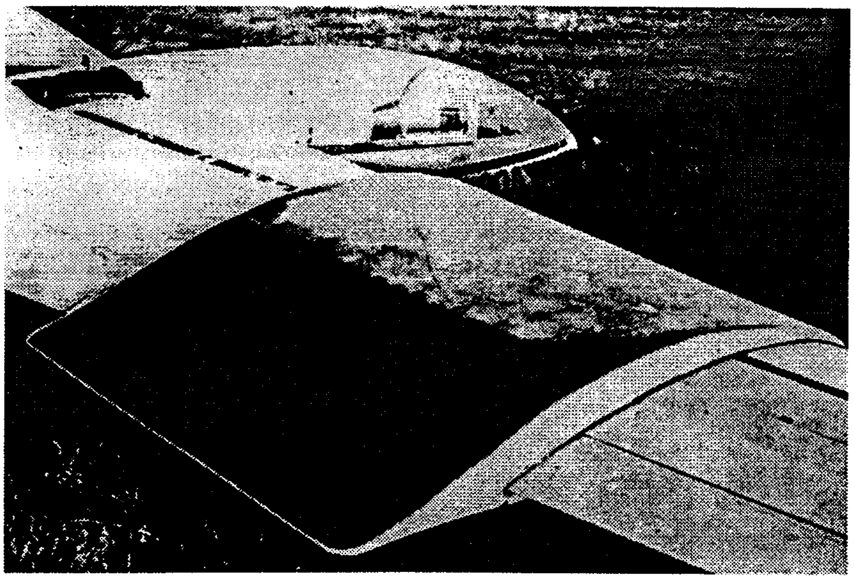

Fig. 2

and in an industrial wind tunnel at equal Reynolds numbers were performed. The results turned out to be identical [30, 31]. Figure 2 shows a visual picture of the boundary layer on a cup fixed to the glider's wing in flight. The black area corresponds to a turbulent state of the boundary layer, and the white area refers to a laminar state.

The stability characteristics of the Blasius boundary layer relative to three-dimensional disturbances were studied experimentally. A strong effect of the nonparallel character of flow was shown in comparison with other computations [32, 33]. In the vicinity of the lower branch of the neutral-stability curve, the boundary layer was found to be more stable to three-dimensional disturbances than to two-dimensional ones.

In the course of experimental studies of the structure of a plane boundary layer with positive pressure gradient, microseparations, along with Tollmien–Schlichting waves, which are indicative of the possibility of realizing the transition mechanism proposed by J. I. Taylor, were discovered [34].

An important stage in the development of laminar–turbulent transition theories is the determination of the initial amplitude of unstable waves, i.e., the solution of the "receptivity" problem. A comprehensive experimental study of the receptivity of a flat boundary layer relative to acoustic disturbances was performed in [35, 36], and that of a three-dimensional layer under the action of three-dimensional vibrations, surface roughness, and in scattering the acoustic wave on localized vibrations were considered in [37, 38].

In many technical devices, their members (for example, turbine blades) are under conditions of gas flow with high turbulence. The breakdown process in a boundary layer is due here to mechanisms that are different from the case of weakly turbulent external flow ("bypass" transition according to Morkovin's terminology). At ITAM, a large series of experimental investigations of the laminar–turbulent transition in a boundary layer at a high level of free-stream turbulence was carried out. A new type of localized perturbations (puff structures) was discovered. Quantitative data on the characteristics of the interaction between these disturbances and Tollmien–Schlichting high-frequency waves (secondary instability) were obtained. Two different physical mechanisms of interaction leading to different scenarios of the laminar–turbulent transition were found to exist [39–42].

The process of the onset of turbulence in spatial boundary layers is much more complicated compared with two-dimensional ones because of the excitation in them of unstable waves attributed to secondary flows, together with Tollmien–Schlichting waves damping in the region of negative pressure gradients. In recent years, many teams of researchers throughout the world have dealt with this process.

Based on unique techniques of generating controlled perturbations in a three-dimensional boundary layer, a complete set of boundary-layer stability characteristics was obtained using a swept-wing model with respect to stationary (longitudinal vortices) and traveling modes of secondary flow instability [43–47]. Under different experimental conditions (airfoil with large angle of leading-edge sweep which is in flow at large negative angles of attack), the evolution of traveling waves in the linear region upon their excitation by a longitudinal acoustic field was studied [48]. The experimental data on the development of disturbances and on the laminar–turbulent transition in a spatial boundary layer in a supersonic flow about a swept-wing model were studied for the first time [49]. It is noteworthy that a negative pressure gradient suppressing Tollmien - Schlichting waves occurs in flow about a supersonic airfoil. A laminar–turbulent transition is therefore due to secondary flow instability waves. At a stage that directly precedes the onset of stochasticity, the secondary instability of longitudinal vortices occurs under certain conditions. The process was studied in [50–53].

Supersonic Flows. In a parallel-theory approximation, new types of characteristic oscillations, namely, oscillations degenerating at large distances from the boundary of a boundary layer into periodically steady-state sound waves and also upstream disturbances were discovered and analyzed theoretically for the first time in [54]. Recent results agree with experimental data [55]. The development of disturbances in a boundary layer with allowance for the nonparallel character of flow was considered theoretically in [56]. The effect of nonparallel flows on the degree of disturbance enhancement appeared to be weak. The data on the interaction of acoustic waves with a boundary layer were summarized in [56, 58]. In particular, it was established that the amplitude of sound-wave-induced disturbances inside the layer can exceed its intensity severalfold.

In recent years, theoretical investigations of nonlinear resonant wave interactions have been started and the asymmetric wave triplet consisting of the fundamental instability wave and subharmonics has been studied. At supersonic velocities and a given frequency of the fundamental wave, the spread in the wave numbers turned out to be considerably smaller compared with subsonic flows [59].

The technique of excitation of controlled disturbances made it possible to obtain quantitative data on the stability characteristics in a supersonic boundary layer that have become reference data in approbation of the methods of their numerical computation [60–63]. The development of disturbances at the nonlinear stage was studied for the first time, and a number of specific features typical of supersonic speeds were revealed. The subharmonic character of the nonlinear wave interaction was discovered. However, unlike the subsonic case, the subharmonic resonance was found to occur in asymmetric triads of waves. At a later stage, the process of "two-dimensionalization" was found in which nonlinear interactions led to the degeneration of three-dimensional disturbances to two-dimensional subharmonic ones [64, 65].

Experiments on the receptivity of a supersonic boundary layer to external acoustic disturbances were performed. In [66], three regions of the strongest receptivity were revealed: the leading edge of a model, the vicinity of the sound branch of the neutral-stability curve, and the neighborhood of the lower branch of the neutral curve. The receptivity process in the vicinity of the leading edge was studied in detail, and the coefficients of transformation of external acoustic waves into free boundary-layer oscillations were found [67].

The results of experimental studies of the effect of the pressure gradient, adiabatic exponent, gas dissociation and ionization, longitudinal magnetic field, and of the presence of an entropy layer on the high-speed boundary-layer stability and on a laminar–turbulent transition were described in [68–74].

Experimental data on the stability characteristics of a hypersonic boundary layer in a flat heat-insulated plate at $M = 6$ both under "natural" and controlled conditions were obtained in [75]. In the latter case, disturbances were introduced into a boundary layer using a point discharge source. It turned out that under "natural" conditions, the maximum pulsations occurred near the upper boundary of the boundary layer, their amplitudes having been by more than an order of magnitude greater than the disturbance amplitudes in free flow.

Experimental investigations of the development of disturbances in a shock layer on a flat plate in flow of a hypersonic gas ($M = 21$) were carried out under "natural" and controlled conditions for the first time. Artificial wave packets were excited using an obliquely cut gas-dynamic whistle [76]. All basic stability characteristics were obtained. In particular, a maximum pulsation intensity was found to occur near the shock wave [77].

As a result of the measurements performed on two flying laboratories created with the use of commercial meteorological rockets, under conditions of solid-propellant rockets, new field data on the local heat-flux peaks

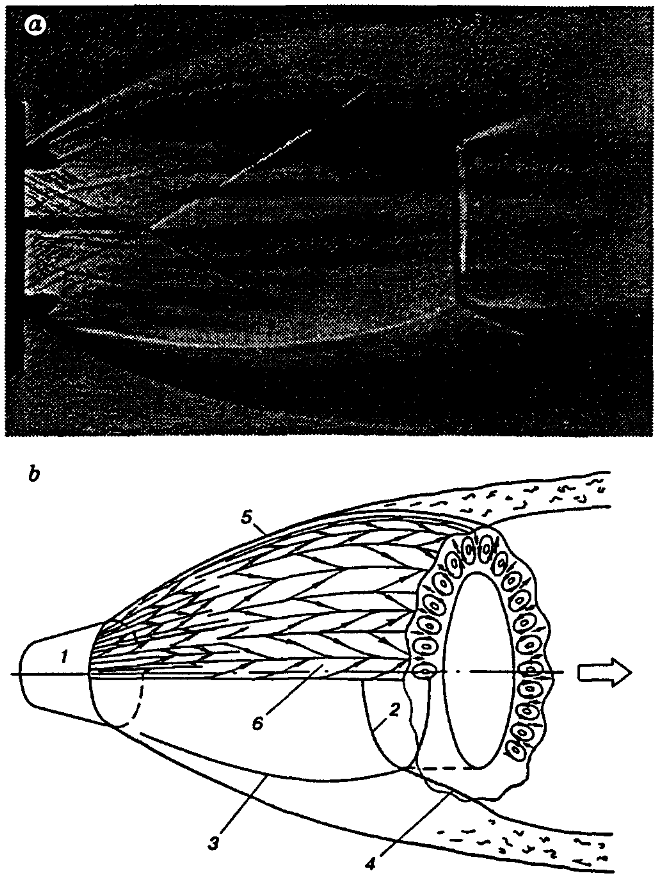

Fig. 3

in the zones of separation of supersonic boundary layers, laminar–turbulent transition, relaminarization, the laminar–turbulent transition interaction and detachment, etc. were obtained in [78–81].

In experimental studies of the structure of supersonic axisymmetric underexpanded jets, the stable azimuthal nonuniformity in the distribution of gas-dynamic parameters was revealed [82, 83]. This was caused by the presence of longitudinal vortices, which is seen in flow visualization (see Fig. 3). Figure 3 shows schlieren photographs (exposure 1/30 sec) of a supersonic underexpanded jet issuing from an axisymmetric nozzle (a) and a schematic view of longitudinal vortex structures at the initial section of the jet (b): 1) nozzle; 2) Mach disk; 3) hanging shock wave; 4) reflected shock; 5) jet boundary; 6) longitudinal vortices [84]. Experimental data on the spectral composition of disturbances were given in [85]. The authors hypothesized that longitudinal vortices are formed owing to the Taylor–Görtler instability in a mixing layer. The related computations within the framework of a weakly linear stability theory supported this hypothesis. In particular, the interaction of disturbances in resonance triads was established to give rise to a considerable enhancement of spiral models in the forepart of the jet. Within the framework of the above-mentioned theory, the self-action and the paired combined interaction of unstable disturbances were investigated [86–96]. Experiments showed a substantial effect of the initial data (level and character of the surface roughness of a nozzle) on the formation and development of longitudinal vortices at the leading edge of the supersonic jet [97, 98].

The stability of compressed layers of flow mixing, including those with a large temperature difference, was studied theoretically. The compressibility was found to lead to the stabilization of vortex disturbances and to the appearance of acoustic modes with supersonic phase velocities. The instability zone of the shear mode turned out to expand for a hot jet and narrow for a cold one, while the acoustic mode appeared to be always stabilized. The initial stages of nonlinear development of shear waves were in progress [99, 100]. The results of experimental studies of wake stability behind a flat plate in flow of a supersonic gas were given in [101–103].

3. Turbulence. The propagation of admixtures in a boundary atmospheric layer was studied [105] based on the concept of simulation of complicated turbulent flows by transport equations of turbulent stresses and turbulent heat flux [104]. The statistical characteristics of turbulent flow in a rotating annular tube were determined. The suppression of turbulence under the action of torsion was explained [106].

In writing the averaged equations of motion, the mechanism and conditions of generation of large-scale structures in rotating temperature-stratified layers [107, 108], the reasons for the appearance of spiral turbulence [109], and the effect of long-term memory of the flow prehistory on heat-transfer processes at supersonic velocities and in the presence of local detachment and reattachment zones [110] were studied based on the previously developed turbulence model with the use of a nonsymmetric stress tensor. The recently discovered [112] separation of the heat-exchange intensity coefficients into discrete levels in a sound field upon rotary anisotropy of supersonic flow was accounted for qualitatively [113].

Many authors have been performing a numerical simulation of complicated supersonic turbulent flows to evaluate the applicability of various turbulence models and to improve them. Complex two-dimensional supersonic turbulent flows with shock waves, detachment zones, and expansion waves were studied in [114, 115] based on numerical integration of Favre-averaged Navier–Stokes equations. To close the system of equations, the C–ω model of turbulence was employed. The use of a more accurate scheme gave satisfactory agreement between computational results and experimental data (see the review by Zheltovodov [116]).

Experimental data on the development of supersonic turbulent boundary layers under the action of large adverse pressure gradients were given in [117–123]. The relaxation zone was found to be extended by more than an order of magnitude after passage of a fan of rarefaction waves than after passage through the shock wave. Mass-flow pulsations were shown to be considerably suppressed under the action of a negative pressure gradient; the effect of this gradient was found to be preserved over a large length and is of a complicated character. It was shown that under definite conditions, flow relaminarization is possible, and the criteria of its appearance were proposed for two-dimensional and axisymmetric bodies.

4. Separation of Boundary Layers. The link between boundary-layer separation phenomena and its instability [1] was supported by a large number of experiments performed at subsonic flow velocities with detailed flow structure measurements [124–135]. Whatever the conditions under which the separation occurred (the wing at a large angle of attack, steps and protrusions on the surface, laminar separation with laminar or turbulent attachment, and turbulent separation), its formation was shown to be connected with wave processes in a shear layer at the external boundary of the separation zone. At the initial stage, wave processes are well described by the linear theory. In studying the nonlinear stage of disturbance development, the subharmonic excitation of a wave with a large width in the wave spectrum of oscillations was revealed. In "receptivity" experiments, local flow zones in which vortex disturbances are generated were found. In a study of the global separation at a "two-dimensional" wing [136], the three-dimensional character of flow — the presence of large-scale vortices in the wing's plane (see Fig. 4) — was discovered; variation of the conditions at the wing tips did not change the general picture.

Complex investigations of the turbulence and heat-transfer characteristics were performed on models of plane separate flows in three ITAM wind tunnels. The effect of Mach and Reynolds numbers and shock interference on relaxation zones behind the attachment and the effect of the separation zone on upstream heat transfer were examined, and also the specific features in the relationships between the distributions of peak values of the turbulence and pressure characteristics in detachment and attachment zones were revealed [136, 137]. An important feature of turbulent flows in the region of intense external gradient action — the formation of longitudinal structures imposed on a turbulent field — was studied in [139]. Measurement results of the flow characteristics in detachment zones initiated by shock waves, which were obtained in a large series of experiments, were reported in [116] in comparison with calculations performed using various turbulence models.

5. Aerogasdynamics of Multicomponent and Two-Phase Media. A specific feature of such media is the presence of several phases and components in the flow which can exchange intensively by mass,

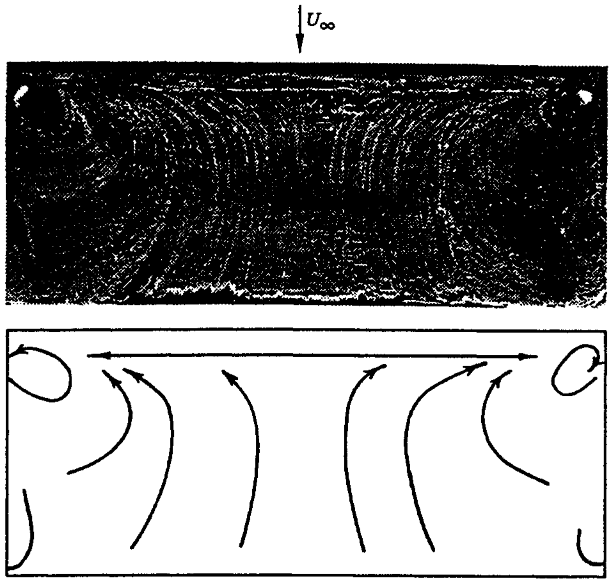

Fig. 4

energy, and momentum, thus exerting a significant effect on the motion of the entire mixture. At ITAM, shock-wave processes in gas mixtures with solid particles were extensively studied [140–142]. The following results were obtained:

• All conservation laws describing the motion of suspensions in air were found, and their types were determined for various solid-phase concentrations. This made it possible to pose correctly and to solve a number of problems of the shock-wave structure in multicomponent gases [142, 143].

• The theory of combined breakdown that takes into account the final particle size was created, and this allowed one to construct a through-computation method for such breakdowns [144].

• A discrete-continual model [145] for flows with intersection of particle trajectories was developed, and the stability of steady-state flows of a mixture in the field of gravity forces was proved. The issues of the formation of caustics in a pseudogas of particles were considered, the criteria of their appearance were found, and the number of particles in a caustic was shown to be proportional to the volumetric particle concentration and, consequently, the mean solid-phase density was shown to be a finite quantity. The link between the theory of caustics and the known concept of a ρ-layer was established [146].

Within the framework of the discrete-continual model, the Euler–Lagrange method of computation of unsteady-state flow of a gas–particle mixture in one- and two-dimensional cases in the presence of the intersection of particle trajectories was devised and realized in the form of a code [145].

As a result of the solution of the problem of interaction of a shock wave with a cloud of particles, it was found that at a volume particle concentration of $m_2 \sim 10^{-2}$, a collective shock wave whose appearance is associated with gas deceleration in the particle cloud, is formed before the cloud. The criterion of the generation of a collective shock wave was obtained based on this mechanism. Its formation was shown to lead to a substantial decrease in cloud deceleration. The results of computations of the trajectory of the left edge of the cloud are in good agreement with experiment [147–153], and, for a rarefied cloud ($m_2 \sim 10^{-3}$), the experimentally found variation in the relative Mach number of supersonic flow over the transverse dimension of the cloud was explained. This was found to be caused by gas deceleration in the compression wave occurring in the cloud [149, 150]. In the problem of the motion of a cloud above a flat surface, at distances between them smaller compared with the thickness of the cloud, the cloud was shown to be divided into two bunches. In the case where the distance to the surface was larger than the cloud thickness, the influence of the surface could be ignored. During acceleration, the cloud was shown to flatten along the direction of its motion, and the particles were shown to be carried away from its side boundaries. The interaction of a shock wave with a particle cloud whose boundaries are subjected to small perturbations at the initial moment of time were analyzed. It was shown that perturbations then grow, which leads to the fracture of the cloud into separate bunches. The important role of secondary eddying gas flows that occur as a result of disturbances of the boundaries of a particle cloud was shown [154].

It is worth noting that at ITAM, investigations of shock-detonation processes in gas mixtures with reactive solid particles were extensively performed, but they will be submitted to the journal "Combustion, Explosion, and Shock Waves."

The process of erosive fracture of the surface in two-phase flow is largely determined by the parameters of particles colliding with it. In supersonic flow about pointed bodies, two fundamentally different flow regimes were discovered, depending on the interaction of a particle system with the surface of a body in flow [141].

For the first regime, the boundary condition on the surface of a body that incorporates erosion variation in the process of flow was obtained, and the flow problem with erosion products taken into account in the zone in front of a body was completely posed in [141]. Its solution made it possible to discover the effect of shielding of a body in flow whose essence is the fact that as the flow rate of the c-phase grows, the erosion rate increases, reaches a maximum, and then decreases. A dense dust layer that formed under the eroded surface was shown to hinder its breakdown. In this case, the convective mechanism of energy transfer was shown to be replaced by a diffusive one, and the pressure in a pseudogas of particles was shown to begin to play an important role in the dynamics of a multiphase mixture [156, 157]. The flow problems for a thin airfoil and wedge breakdown in a supersonic dusty flow were solved using the proposed model [140].

In the second flow regime, two effects of practical value were revealed:

- Formation, in front of pointed bodies, of leading separation zones by the particles reflected from a body during their flight at a distance exceeding the thickness of a shock layer, which leads to a considerable decrease in body drag.
- Formation of a coating from solid-state metallic particles, which allowed one to propose a new method of coating deposition — "cold gas-dynamic spraying" [156–158].

6. Aerogasdynamics of Flying Vehicles. The practice of designing modern aircraft has created new problems, including those associated with more perfect matching of their members. The interest in studying the physical properties and specific features of the evolution of flows in the regions of matching of aerodynamic surfaces with a view toward developing adequate methods of computation of this complex class of shear flows has been continuously increasing. However, the scarce experimental information on some directions of research of this problem has retarded the creation of an effective method of computation of the designs of flying vehicles and has limited to a considerable extent their direct practical applications. In this connection, in ITAM systematic experimental studies of diverse forms of spatial compressible and incompressible flows in the regions of matching of various intersecting surfaces under conditions of a large number of complicating factors — significant effect of the flow prehistory, presence of the pressure gradient, longitudinal and transverse curvature of surfaces to be matched, flow asymmetry, interaction of an oblique shock wave with a boundary layer, etc. — have been carried out over several years.

The basic specific features of the development, the physical properties, and the structure of spatial laminar and turbulent near-wall flows in plane and curvilinear longitudinally flowing corner configurations over a wide range of conditions and variable parameters were established [159–164] based on the use of the original methods developed and the tools of diagnostics. In particular, the mechanism of formation of eddy flows was revealed both under conditions of strong turbulence and over the length of a laminar-turbulent flow region [163–165]. The important role of the geometry of the leading edge of a corner configuration and of the asymmetry of intersecting surfaces was discovered, directly and indirectly substantiated, and explained [166, 167]. The conditions of interaction and joining of two spatial angular zones in a rectilinear channel were studied experimentally, and the requirements for the choice of minimum transverse dimensions of such channels to exclude negative phenomena were formulated in [166].

The effect of enhancement of the hereditary features of spatial flow (flow memory) near the line of matching of two surfaces [168] compared with the two-dimensional region [167–171] was discovered, and

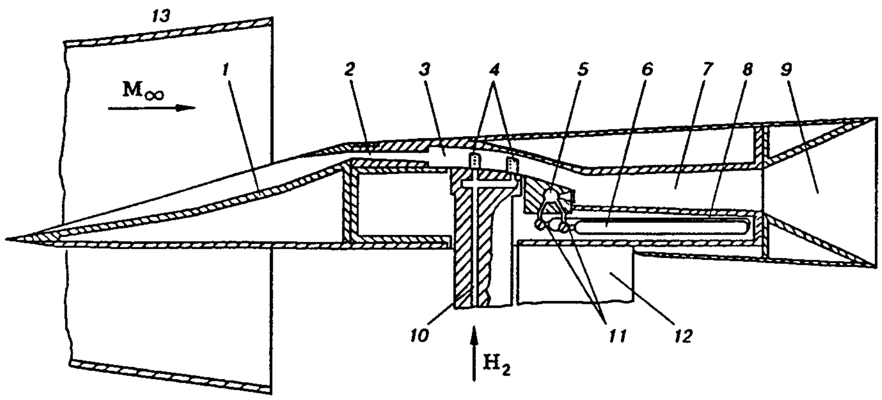

Fig. 5

dominating mechanisms that are responsible for the decrease in the relaxation rate of the flow in the first of the indicated regions were found. Its basic cause was shown to be the formation of longitudinally developed vortices as basic carriers of information on disturbances [169].

The understanding of the structure and physical mechanisms that govern flows in angular zones made it possible to find a reasonable (from the standpoint of minimum drag) shape of matching of a wing and a fuselage of a schematic design of an aircraft compared with the initial one, which ensures a decrease in the drag by several percent [172–174].

The key specific features of the structure of a spatial separate flow initiated by the interaction of an incident oblique shock wave with a developed turbulent flow were revealed in a corner configuration in [175–178] and in a rectangular half-channel in [179–181]. Correlation relations for determination of geometric characteristics of the detached flow regions being realized were obtained.

The classes of flow problems for a system of bodies refer to the most complicated problems of aerodynamics. At ITAM, detailed experimental data on aerodynamic interference of two-step systems upon their separation were obtained, and the specific features of the flow structure were clarified. These data enabled one to verify mathematical models with the use of not only integral but also local parameters [182, 183].

The flows in plane axisymmetric nozzles under conditions of external supersonic airflow were studied theoretically and experimentally with a view toward designing their optimal shapes. Control methods for the contour of a nozzle in noncomputational regimes and also a method of determining experimentally the internal force characteristics of a nozzle in external supersonic flow were proposed. An extended zone of separation of the external flow near the edge of a short shell was found, and it was established to have a spatial structure. A computational method for subsonic and supersonic flows in nozzles was developed, and the computations performed agreed well with experimental results [184, 185].

The three-dimensional boundary layer on the compression surfaces of convergent inlets was studied [121]. The nonseparation flow was shown to be realized under conditions of very large longitudinal pressure gradients [120].

According to the literature data, at present the ultimate Mach number of flow reached in experiments on the models of hypersonic ramjet engines (HRE) is equal to 8.0. Promising HRE are assumed to have $M = 8$ and, therefore, attempts are being made in many laboratories throughout the world to design models of a next-generation HRE and to study the physical processes proceeding in them. To this end, an experimental model of a hypersonic rocket-ramjet engine (HRRE) (see Fig. 5) whose distinctive feature is a packet of five rocket microengines operating on a hydrogen–oxygen mixture and built into a ramjet channel was designed. The model is intended to be employed in $M = 8$–18 experiments. The designations in Fig. 5 are as follows: 1) removable inlets; 2) initial section of the combustion chamber; 3) combustion chamber; 4) injector belts for fuel feed; 5) unit of the rocket engine; 6) reservoir with O_2; 7) end section of the combustion chamber; 8) reservoir with H_2, 9) removable nozzle; 10) pneumatic line for H_2 supply; 11) line for H_2 and O_2 supply for

8) reservoir with H_2, 9) removable nozzle; 10) pneumatic line for H_2 supply; 11) line for H_2 and O_2 supply for the engine; 12) three-component balance; 13) nozzle of the wind tunnel. Computed estimates showed that, for the flight M equal to 12, the efficiency of this engine is much higher than that of the rocket one [186].

In an IT-302M pulsed wind tunnel, "cold" and "hot" tests of an HRRE model were performed in a ramjet regime with the flow M equal to 10, 12.2, and 13, excess-air ratio 1.0, and the following stagnation parameters: $P = 150$–400 bar and $T = 2100$–2300 K. The pressure distributions over the engine channel were measured at various moments of time, and the convergence in time of the distributions of relative pressures to a steady regime was established. Processing of the experimental data obtained showed that the combustion of gaseous hydrogen occurs in a supersonic air flow [187–189].

Despite the fact that studies of the integral aerodynamics of hypersonic vehicles have been performed for several decades, they are still important. At present, the search for optimal configurations of flying vehicles that ensure maximum flight efficiency is possible only with the use of simple mathematical models based on the method of gas-dynamic design [190, 191].

Experimental and theoretical studies of the integral aerodynamic and integral thrust-aerodynamic characteristics of hypersonic vehicles (HV) and aerospace vehicles of various configurations were carried out. Along with a study of the basic characteristics, data on the general effectiveness of some aerodynamic concepts which are of interest for design of promising hypersonic vehicles with ramjet engines (HV with RE) were obtained.

The specific features of the aerodynamics of a hypervelocity aircraft were studied in tests of the models in wind tunnels at supersonic and low subsonic velocities (M = 2–6 and 0.15) [192–196]. The distinguishing feature of these experiments was the necessity of carrying out complicated investigations of RE models with internal-flow systems, with a simultaneous measurement of both forces and moments using aerodynamic balance and flow-rate characteristics of inlets. The technique of aerodynamic tests of these models at high supersonic velocities was improved considerably. As a result, some general trends in variation of the lift-to-drag ratio of hypersonic aircraft with an increase in maximum flight speeds were revealed [196].

In computational investigations, the specific features of the formation of the resulting thrust-aerodynamic forces as applied to HV with RE and with a hypervelocity combustion chamber (HRE) for the flight M equal to 4–15 were studied. In [192, 197–201], approximate computational methods were developed based on the polygonal idea of aerodynamic configuration with the use of a small number of triangular and multiangular flat panels so that, for polygonal configurations, which schematize and approximate HV configurations, the major properties of the layout of an aircraft were simulated. The resulting thrust-aerodynamic HV characteristics with various locations of HRE tracks in combination with an airframe were calculated in [195, 196, 198, 201, 202]. Attention was primarily given to the traditional HV layout with an HRE unit under a wing or lifting body, which is used, for example, in the NASP, HOTOL, SANGER, TU-2000, and other projects. For such configurations with flat inlets, the specific features of the flight, in particular, the so-called "channel" instability, which was not previously noted, were revealed [192, 197, 198, 201]. Alternative HV configurations with side positions of HRE channels [195, 196] which do not have, for example, the aforementioned instability were examined as well. The computational results and the experimental data obtained allowed one to perform a comparative estimation of the flying properties of the configurations considered [195, 197–202]. The developed computational techniques realized as software and handed over to various institutions were applied effectively to determine the integral thrust-aerodynamic characteristics in a preliminary design of HV with HRE [201].

In ITAM investigations, the methods of gas-dynamic design developed for the creation and study of the specific features of HV configurations with RE with new types of inlets of all-around compression, in particular, with convergent inlets, were employed. Based on a V-shaped lifting wing — Nonweiler wavelet — a HV configuration with RE with a convergent inlet from V-shaped bodies was constructed [202, 203]. This configuration is of interest, because it offers the possibility of combining useful effects of the position of the inlet under the lifting surface and of the side position of ramjet channels. Convergent inlets, which are similar to the so-called three-dimensional ones with side compression studied at NASA Langley and the Baranov Central Institute of Aircraft Motor-Building or their modifications, were designed [203, 204].

Aerodynamic characteristics of wavelets constructed on the basis of flat flows near a wedge and axisymmetric flows near the annular cone and the integral heat fluxes to their lifting surfaces were analyzed [205–208]. The optimal characteristics that ensure a maximum lift-to-drag ratio under given restrictions on the magnitudes of the volume and lift coefficients and of the levels of heat fluxes were found. The optimal lift-to-drag ratio was shown to be dependent weakly on the shape of the transverse contour of the lower surface (either flat, or transversely-convex or convex-concave). This gives one freedom in the choice of wavelet models studied as the foundation for construction of the forebody or configuration of a HV with RE as a whole, because it allows one to combine various flat or convergent inlets with them without a considerable decrease in the lift-to-drag ratio compared with an optimal one.

The application of the principles of arrangement of small-scale flows, which are used in gas-dynamic design of convergent inlets, to lifting surfaces with all-around compression enabled one to develop a class of swept lifting configurations with transversely convex surfaces producing three-dimensional convergent supersonic compression flows [191, 203]. As computations showed, new configurations ensure a higher-level longitudinal effect of compression of a jet captured by an inlet in comparison, for example, with compression flows formed about HV forebodies with conventional plane or transversely convex lower surfaces. To the same class refer convergent wavelets [203] constructed based on axisymmetric compression flows in inner cones. The new class of aerodynamic configurations can find applications in high-speed vehicles with RE, because the effect of longitudinal compression can be used to increase the thrust-aerodynamic effectiveness of promising hypersonic and aerospace vehicles.

The theory of construction of airfoils and wings within the framework of the model of an ideal gas was further developed. A number of problems of construction of airfoils realizing a maximum critical Mach number under given restrictions on the lift force were solved using the projection-optimization method of solving optimization problems with a restriction in the form of a partial differential equation. A method of numerical solution of boundary-value gas-dynamic problems was developed based on the variational principle. This method is based on the concept of flow using a functional whose extremals are the flow equations of an ideal gas. The sign constancy of its second version for subsonic flows was shown. Some problems of airfoil construction were solved by minimizing the constituent functional [212, 213]. The algorithm of numerical solution of boundary-value problems of aerogasdynamics was solved based on the boundary-element method of solving a nonlinear integral equation, which is equivalent to the gas-dynamic equation [214–216]. In [217, 218], new methods of describing free boundaries of flows were devised using parametric polynomials which exclude oscillations of the solution, thus making the optimization problem regular. These methods enabled one to create a packet of applied programs for prediction of optimal two-dimensional configurations subject to given aerogasdynamic and geometric limitations and to solve a series of problems of construction of subcritical and critical nonseparation airfoils possessing either a maximum lift force or lift-to-drag ratio, or a minimum pitch moment, with restrictions on its area and thickness [219, 220].

For a finite-span wing in a subsonic incompressible flow, the effect of eddy structures on its aerodynamic characteristics was investigated based on the vortex pattern proposed in [221] and allowing one to formulate the shedding conditions for an eddy cover, which are similar to the Joukowski–Chaplygin conditions at the back edge [222, 223]. For a finite-span wing in supersonic flow, exact analytical solutions of the direct and inverse problems of aerodynamics were derived within the framework of the linear theory, including the class of limited functions, with satisfaction of certain conditions of the Joukowski–Chaplygin type imposed on the smoothness of the governing parameters. The problem of a wing in flow with completely subsonic leading edges and also the problem of the tip effect, with Joukowski–Chaplygin conditions on the subsonic part of the leading edge, was solved analytically [224, 225]. In [226, 227], the possible solution of the inverse problem in the class of limited functions was substantiated, and examples of the construction of finite-wing surfaces under given load on them were given.

To calculate the aerodynamic characteristics of wings of complex configurations in a supersonic flow, software was created based on the linear theory. The elaborated algorithm of solving direct problems of aerodynamics made it possible to solve a number of new optimization problems for a finite wing: optimization with limitations in the form of inequalities, under self-balance conditions, and with a maximum lift-to-drag ratio. The investigations allowed one to find wing configurations with high lift-to-drag ratio for which the effect of a "thrusting" leading edge was revealed [228–232].

Algorithms allowing the calculation of a spatial compressible boundary layer in a supersonic flow about pointed bodies shaped like a fuselage [233–240] and also of sharp-edged contoured delta wings [241–246] were elaborated to calculate the drag coefficient. In this case, the boundary layer can be laminar, transitional, and turbulent. For description of turbulent flow, various algebraic models of turbulence were used, and for determination of the laminar–turbulent transition zone, a simple semi-empirical criterion relative to the momentum thickness was proposed in [236, 244].

For verification of the algorithm and the program of computation of a boundary layer on pointed bodies, the drag coefficients, the Stanton numbers, and the velocity profiles were compared with the results of experimental studies [235, 237, 238]. Satisfactory agreement between computational and experimental data was obtained for ogival-cylindrical bodies. Another series of calculations was performed for a strongly flattened body of bielliptical cross section.

A computational algorithm for a hypersonic flow about a flat plate with zero angle of attack [247–251] and at angle of attack [252, 253] was elaborated within the framework of a complete viscous shock-layer model. Comparison of the computational and experimental density profiles and of the detachment of a shock wave showed their satisfactory coincidence. As the Mach number increased, the thickness of the viscous layer near the plate was found to grow, while that of the inviscid one was established to diminish, and in practice, unlike supersonic flow, the shock-wave detachment is unvaried. The thickness of the shock layer, the friction coefficients, and the Stanton numbers decreased with increasing Reynolds number. With the angle of attack varying from -15 to $+15°$, the static pressure and the density near the plate surface increased, and the Mach numbers behind the shock wave decreased.

The creation of a new generation of aerospace vehicles (satellites, space stations, shuttle capsules, aerospace transport systems, etc.) requires comprehensive analysis of their aerothermodynamic characteristics along the entire flight trajectory. A considerable part of the flight trajectory of promising aerospace vehicles lies in the region of high altitudes where the effects of rarefaction and strong thermochemical nonequilibrium of a supersonic flow are decisive. Experimental simulation of high-enthalpy strongly nonequilibrium rarefied flows is rather problematic and, therefore, at present the required information is mainly obtained by the methods of computational rarefied gas aerodynamics.

The basic equation that describes flows of a rarefied gas, i.e., flows in which the length of the free path of gas molecules is comparable with the characteristic dimension of a flying vehicle, is the Boltzmann nonlinear kinetic equation. At present, the method of direct static simulation (DSS) based on the application of the Monte Carlo methods to the solution of the Boltzmann equation has become a de facto major tool for studying complicated multidimensional flows of a rarefied gas, because this enables one to simulate the effect of a real gas at the microscopic level, i.e., to use physically adequate models of intermolecular interaction and of internal degrees of freedom of molecules and chemical reactions. One more advantage of the DSS method is the possibility of solving multidimensional problems of geometrically complicated aerospace vehicles in flow without the considerable complication of a numerical algorithm.

Economic numerical schemes of the DSS method for spatially nonuniform flows of a simple gas and of a mixture of chemically reactive gases were proposed in [254–259]. Numerical criteria of estimation of the effect of the statistical dependence of the model particles on the calculation results were found [260, 261]. These schemes were verified in solving classical problems of rarefied gas dynamics. Within the framework of the DSS method, models of internal degrees of freedom of molecules were developed based on the quasi-classical theory [262–264] and also a model of chemical reactions with allowance for the oscillational-dissociative interaction was developed [265, 266]. The DSS schemes and models underlay computational instrumentation [267, 268] allowing the solution of various problems of rarefied gas dynamics, for example, flow computations near bodies of complicated shape with allowance for real gas effects [268].

In [269], studies of the problem of aerodynamic control effectiveness at high altitudes were started based on the computational methods developed. Two- and three-dimensional computations of flow about aerospace vehicles with deflected control boards were performed using the numerical instrumentation developed. The flow

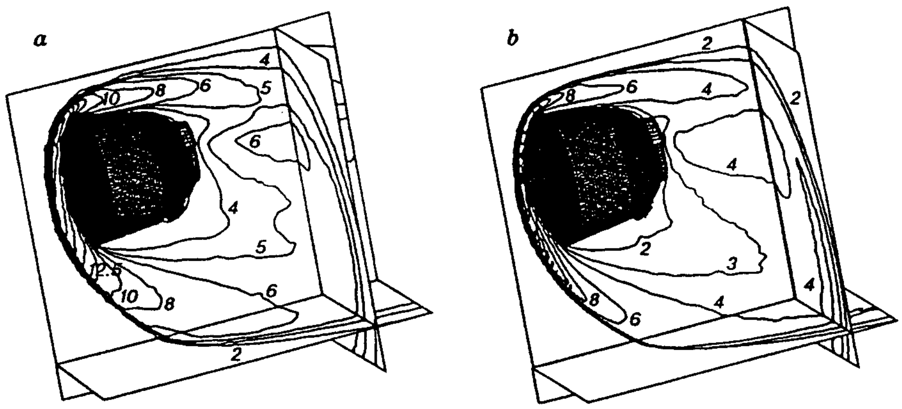

Fig. 6

about models of convex bodies for various Knudsen numbers and the real gas effects on the flow structure near a convex surface were examined in detail, and the distributed aerodynamic characteristics and the efficiency of a controlled board were determined [270–272].

The evolution of a space debris cloud in the upper atmospheric layers (at altitudes from 250 to 80 km) was simulated statistically [273].

An important stage of research was the creation of modern software for computation of the aerodynamics of flying vehicles of complicated shape in transitional and free molecular flow regimes and also data preprocessing and postprocessing. A RAMSES software system was developed for the ESA/ESOC European Space Agency [274], which, according to the opinion of this institution's experts, is one of the best programs in the world for analysis of aerodynamic properties of complex aerospace vehicles in a free-molecular, transitional, and hypersonic continuous-medium flow and is used for exact determination of the orbit altitude, design of a system for monitoring orbit parameters, and for better prediction of the re-entry of spacecrafts.

The efficiency of numerical algorithms of the method of through statistical simulation on modern computers with parallel architecture was tested and analyzed. A new algorithm that provides for a uniform load of processors and reaches a 90% efficiency on 256 processors was elaborated [274]. The flow about the re-entry capsule of the "Soyuz" spacecraft was calculated for various flight altitudes and angles of attack on parallel computers. The results are in good agreement with the available flight data. Figure 6 shows temperature fields in air flow about the capsule (at a flight altitude equal to 85 km) without (a) and with (b) chemical reactions taken into account. The figures refer to the values of the increasing temperature in thousand degrees of Kelvin. The differences show up both in the detachment of the shock wave and in the considerably less gas heating behind it in the presence of chemical reactions.

7. Flow Control. Aerophysical studies reveal the characteristic properties of flows, their role in the motion of bodies in the gas. As a result of the studies of shock-wave processes, the laminar–turbulent transition, etc., unique flow control methods intended for the decrease in power cost of flying vehicles at subsonic and supersonic flow velocities owing to the decrease in the skin friction, wave drag, and in bottom-pressure resistance and owing to the increase in the lift force of vehicles were found.

Subsonic Velocities. Methods of active control of separate flows about wing airfoils, based on the results of study of the flow instability in the region of their formation, were developed. It turned out to be possible to decrease the dimensions of local separation zones by exciting small perturbations by localized sources or by an external acoustic field. The mechanisms of interaction of controlled disturbances and the mean flow that explain this effect were proposed [275, 276]. In the case of global separation in the flow about a wing, the flow was successfully reattached by superimposing an external acoustic field [278–281]. One should note that the flow remained reattached after removal of the acoustic field (hysteresis).

The external acoustic field is an effective means of flow control in turbulent wakes behind bodies in flow as well. This is associated with the presence of coherent structures. This process was considered in detail in [282, 283].

In [283, 284], the results of an experimental study of the effect of an acoustic field on the structure of swirling separate flows about a delta-shaped wing at large angles of attack were given.

The stabilizing action of a single small two-dimensional surface roughness in a laminar–turbulent transition in a boundary layer was discovered in [286] and supported experimentally in [35] (the surface roughness usually turbulizes the flow). This effect was explained by the interaction of Tollmien–Schlichting waves generated in a boundary layer with the waves of this kind generated in the neighborhood of the roughness and, as a result, their annihilation occurred. This method of transition control is, as a matter of fact, a version of the active method proposed by H. W. Lieppmann. The results of ITAM experimental studies of active control methods were summarized in [286].

The stabilizing effect of surface cooling and the destabilizing effect of surface heating in gas flow about the surface are well known. Two teams of researchers in Moscow (headed by V. V. Struminskii and M. N. Kogan) discovered theoretically the stabilizing action of heating of the leading edge of a body in flow on the stability of a boundary layer downstream. Experimentally, this effect was supported in [287] upon excitation of controlled disturbances. It was attributed to the propagation of a heat screen in a boundary layer above a relatively cold surface. In the experiments reported in [288], the possibility of boundary-layer laminarization under "natural" conditions by successive displacements of localized sources of surface heating was shown. The stabilizing action of localized heat supply in a supersonic gas flow about the model was described in [289].

It is well known that a weak streamwise ribbing of a surface (riblet) leads to a decrease in turbulent friction drag. Attempts to apply this method to transition control at the linear stage of disturbance generation produced a negative result. However, riblets were found to stabilize considerably the transition process at a strongly nonlinear stage when they are placed in the zone of formation and development of Λ-shaped structures. In addition, riblets were found to change strongly the structure of longitudinal vortices ("stems" of Λ-shaped structures). The same effect was revealed in studying the development of the instability of longitudinal vortices formed under different conditions: Görtler vortices, stationary vortices of secondary-flow instability in a spatial boundary layer, etc. A concrete method of transitional boundary layer control in developing stationary vortices of different nature was proposed in [290–295].

Supersonic Velocities. Studying new principles and methods of control of aerophysical processes in supersonic flow remains important, despite the many publications from the early 1960s up till now [296]. The control methods of supersonic flow about bodies can be grouped as follows:

- Mechanical methods using aerodynamic needles with various shaped tips. The presence of thin needles in front of a body in supersonic flow leads to variation in the flow character and, as a consequence, to the formation of a region of backward flows before the body, which causes a considerable decrease in body drag.
- Gas-dynamic methods which are realized by ejection of the mass of different physical states (either gas or liquid or a two-phase flow like a gas with small solid particles) [297, 298]. It was established that flow rearrangement occurs similarly to that occurring with the use of mechanical methods, and, for some bodies, is the most efficient from the viewpoint of drag decrease.
- Mechanical methods in combination with gas-dynamic ones [297] in which the formation of some zones and their control are performed by burning propellants of various kinds, thus decreasing the nose and base drags. This method can be effectively used to control flight trajectories of aircraft.
- Methods of forming local heat zones in supersonic gas flow before a body. At ITAM, experimental studies of the formation of such zones using a high-power optical charge and also of the flow about bodies under these conditions were performed in [299]. Laser energy release was shown to change significantly the flow structure for a body in flow and, consequently, decrease its drag. Based on numerical simulation in a three-dimensional approximation, it was found in [300] that the presence of a thermal zone on the symmetry axis of a body in flow makes it possible to vary the moment characteristics. The source of the initial heat zone used was similar to that employed by V. M. Levin and his colleagues in analysis of flow problems in a two-dimensional approximation.

Conclusion. Many important problems of aerodynamic investigations which were posed in the late 1980s [1] were successfully solved at ITAM in the last decade. At the next stage, the problem of aerodynamics:

(1) Improvement of the existing experimental base and measurement methods and the creation of new ones allowing one to perform studies under conditions as close as possible to natural ones.

(2) Improvement of and search for fundamentally new control methods for aerogasdynamic processes with the aim at decreasing the body drag and improving the thrust and economic characteristics of power devices.

(3) Development of fundamental investigations of the thin structure of aerophysical phenomena for creation of new technologies in various fields of engineering.

(4) Mathematical simulation of complicated aerogasdynamic phenomena occurring under real conditions of flow about flying vehicles and in flows in engines, and in new technologies.

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