POSSIBILITY OF SIMULATING HYPERSONIC FLOWS ON HIGH-PRESSURE ADIABATIC GASDYNAMIC COMPRESSION SETUPS

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The prospects for the development of aviation and aerospace technology require the creation of new ground-based aerodynamic installations, permitting simulation of flight conditions in a range of Mach numbers M = 6-24 with Reynolds numbers remaining close to the natural values. As follows from [1], for complete simulation of flow with the indicated Mach numbers, it is necessary to have Reynolds numbers, scaled to the diameter of the working part of the nozzle, at a level of 10^9 for M = 6 and $3 \cdot 10^8$ for M = 13.

The construction of commercial installations for aerodynamic tests of prospective aircraft in a range of natural Re numbers, according to estimates of American specialists, will require the expenditure of hundreds of millions of dollars and, in addition, a single firing will cost from $1.6 to $3.4 million [1].

A promising course, providing the closest approximation to natural Re numbers, is the creation of pulsed aerodynamic installations, which are inexpensive to construct and to use, with high starting gas parameters in the forechamber. The pulse operational mode makes it possible to obtain high starting parameters of the outflowing gas and, as a result, high Mach and Reynolds numbers in the working part.

At the present time, record high parameters with respect to limiting Mach numbers at pressures up to $p_0 \approx 400$ MPa in the forechamber have been obtained in pulsed installations. However, the Re numbers simulated in these installations are already inadequate.

The intrinsic inadequacy of existing pulsed systems, operating in a time range of more than tens of milliseconds, stems from the continuous drop in gas pressure in the forechamber during the outflow process, as a result of which these installations operate in a regime of time-dependent flow parameters. An increase in the starting pressure in the forechamber increases the Reynolds number, but due to real gas effects, it leads to an additional increase in the rate of decrease in the gas parameters [2], which complicates the interpretation of the results obtained and decreases already low utilization factors of the working gas.

Existing pulsed installations make use of different methods for heating the working gas, which can be arbitrarily separated into two groups. The first group makes use of special auxiliary systems, which heat the gas from an external heat source: electrical discharge, resistance, hot blast stove systems, and systems using chemical energy. The second group characteristically uses natural heating of the gas as a result of adiabatic compression.

Installations in the first group required creating special additional powerful energy sources or heat exchangers, operating under high pressure conditions and in corrosive media (while operating in air). Electrical discharge and chemical heaters greatly contaminate the working gas. Resistance and hot blast stove systems require a special complicated system for cooling and thermal insulation, which provide for structural strength at high temperatures and increased volume of the installation operating at high pressures and in view of the duration of the heating processes, are subjected to strong corrosive action, which eliminates the possibility of using air as a working gas.

Adiabatic compression installations use the so-called free piston principle and do not have the disadvantages indicated above; but, having in this sense a number of advantages, they do, however, require solving problems related to the dynamics of gas compression. Thus, a Long-Shot type installation [3-7], in order to maintain the adiabatic compression of the gas during piston recoil, is equipped with a complex system consisting of a set of valves,

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located on a special valve panel. The valves operate under extreme conditions and are subjected to quite rapid erosion, which contaminates the flow, and the necessity of replacing them often limits the limiting temperature and pressure of the gas in the forechamber. When the gas flows through the valve, a significant amount of heat is lost. During the working cycle after the gas is transferred into the forechamber, the piston in existing installations undergoes a damped periodic motion, which leads to parasitic oscillations of the installation, complicating the experiment. The maximum pressures in the forechamber, obtained on such setups, attained 400 MPa [1, 5] and are at the present time the highest attainable pressures.

Calculations of the gasdynamics of gas outflow in the presence of ultrahigh starting pressures show the expedience of further increasing the starting pressures in the forechamber, since an increase in the gas density and the use of the potential energy of molecular repulsion make it possible to increase the Mach numbers attainable at the saturation point and have a very favorable effect on the Reynolds numbers that can be attained for the given scale of the installation [2, 4]. We note that this greatly affects Mach numbers beginning with pressures near 400 MPa and, therefore, existing installations still make little use of these effects.

An important advantage of installations with ultrahigh pressure is the possibility of obtaining high Mach numbers on the saturation line with low temperatures in the forechamber and in the critical section. Thus, the stored specific enthalpy at a pressure of p_0 = 1500 MPa and temperature T_0 = 2000°K is the same as in an ideal gas at T_0 = 3150°K (see [2]). When the magnitude of the outflow velocity is maintained, this has a favorable effect on the stability of the critical section and also decreases the heat losses into the wall of the forechamber.

The goal of the work carried out recently at the Institute of Hydrodynamics and SKB GIT, Siberian Branch, Academy of Sciences of the USSR, was to prove the possibility of further increasing the parameters of the gas in the forechamber, improving the technical and operational characteristics of systems with a free piston.

This work resulted in the creation of the A-1 adiabatic compression installation, which, having small dimensions, has characteristics that permit obtaining flows with natural Re numbers by increasing its scale size. One of the basic elements of the installations is the adiabatic compression tube, with a working length of about 1.8 m and an inner diameter of 500 mm, equipped with a heavy wedged piston, described in [8]. Since the piston construction used permits stopping it at the position of maximum compression, it is possible to solve two problems immediately: to free the installation of the valve system and to eliminate the oscillations mentioned above.

The pulse, arising with the acceleration and deceleration of the piston, is extinguished by a special compensator, as a result of which the displacements of the stem during compressure do not exceed 0.1 mm without the transmission of any forces to the foundation of the installation. For existing adiabatic installations, this problem is quite serious. The installation includes a special automatic precompression system, which provides an outflow of up to 40 cm^3 of gas (approximately one-half of the compressed gas) in the constant pressure regime, which permits obtaining a plateau in the parameters p_0, T_0, and ρ_0 in the forechamber in a time from 10 to 150 msec (depending on the diameter of the critical section).

The installation gives a clean, homogeneous flow, uncomtaminated with particles and foreign gases. As follows from [2], increasing the starting pressures from 400 to 1500 MPa at the same temperature (T_0 = 2000°K) increases the Mach numbers, attainable on the equilibrium condensation line, from 15.5 to 18. When the Mach numbers are maintained at a level $M \approx 16$, this increase in pressure leads to an increase in the Reynolds numbers, calculated per unit length, approximately by a factor of 20, and at the same time the gas temperature in the forechamber decreases to T_0 = 1600°K.

The A-1 aerodynamic installation was designed and built for operation at pressures up to $\approx$1500 MPa. Hydrostatic tests, conducted in order to determine the carrying capacity of the structure, showed that plastic deformations appear at pressure of about 2500 MPa. The following maximum parameters were achieved on the installation: p_0 = 1000 MPa, T_0 = 1800°K (operating with nitrogen). The pressure limitation is related to the absence, at the present time, of the necessary source for feeding compressed gas into the system (200 MPa);

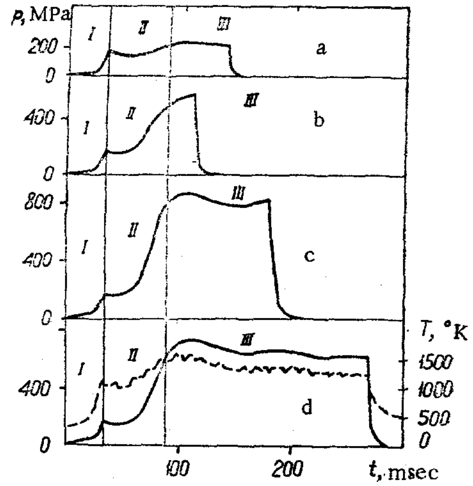

Fig. 1

when the appropriate source is installed, the parameters will increase to their rated values. Studies that will insure the necessary stability of the critical section at such parameters in the forechamber were carried out.

The maximum parameters, obtained during operation with air, do not exceed 500 MPa, and further increases were purposely not made in order to avoid the possible corrosion damage before attaining the rated maximum parameters for nitrogen. During the test and operation time, the installation completed more than 200 cycles without replacement of any parts (except the nozzle inserts) and no residual phenomena, damage, or deviations from the norm were observed.

For the tests, conical nozzles were used with a total flare angle $\alpha = 8°$ and edge diameters $d_{ed} = 13.4$, 15, and 16.4 mm. The diameter of the critical section varied from 0.14 to 0.925 mm. When the hypersonic flow was let out into the atmosphere, Mach numbers near 11 were attained.

Examples of oscillograms of the pressure in the forechamber, obtained under different regimes, for diameters of critical sections equal to 0.805, 0.78, 0.336, and 0.319 mm are presented in Fig. 1a-d, respectively. It is shown that the working cycle of the installation goes through three stages. The segment of the oscillogram I corresponds to gas compression by the free wedged piston with a sharp increase in pressure at the end of the compression cycle up to ≈150 MPa; segment II corresponds to operation of the automatic precompression system, at the end of which maximum pressure is attained in the forechamber. Then there follows a segment with constant pressure III, which is the proper operating outflow regime. For the examples presented, the value of the pressure in the working regime is on the average 210, 540, 810, and 650 MPa for Figs. 1a-d, respectively. It is evident that the pressure oscillograms have a plateau, within which there are several oscillations, whose amplitude, however, does not exceed 5% of the magnitude of the average pressure. We note immediately that these oscillations are a result of some nonfundamental structural properties of the system feeding the installation which in the future could be greatly decreased. After the segment with constant parameters, there is a sharp drop in pressure, corresponding to the end of the operational cycle.

Figure 1d shows an oscillogram of the gas temperature in the forechamber (dashed line). The observed drop in temperature toward the end of the working regime is explained both by losses of heat through the walls and by some properties of the temperature sensor. This drop does not exceed 2.5°K/msec and can be decreased by introducing thermal insulation into the forechamber. As is evident from the oscillograms, for a critical diameter $d_* \approx 0.3$ mm, the time for maintaining the constant parameters attains on the setup 180 msec, while for $d_* \approx 0.8$ mm, the time is ≈30 msec.

Figure 2 shows a selection of frames from a shadow motion picture of a hypersonic flow with $M \approx 11$, obtained on the A-1 installation, flowing out into the atmosphere past a Pitot tube. The pressure in the forechamber is $p_0 = 550$ MPa, $d_* = 0.78$ mm, and $d_{ed} = 13.4$ mm. In this experiment, nitrogen, compressed from a starting pressure of 0.95 MPa at room

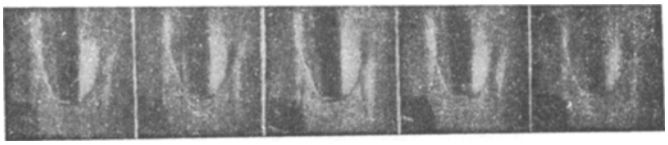

Fig. 2

temperature 290-295°K, was used. The time between the frames in the motion pictures shown is 5 msec. It is evident that there are no significant changes in the nature of the pattern, such as any noticeable inhomogeneities in the core of the flow, within a time of 20 msec.

Let us now compare the possibilities of existing systems with the A-1 installation. In the literature (see, for example, [9]) devoted to pulsed tubes, it is often justly stated that during operation with constant forechamber volume, the pressure drop does not greatly affect the Mach numbers of the flow during the working regime, and for this reason, it is not important for accuracy in reproducing the Mach numbers. This is true only in the case in which the parameters of the flow in the working part at the beginning of the regime are sufficiently far from the saturation line, since in the opposite case, during the working cycle, gas condensation can begin near the model past which the flow occurs.

As far as the Reynolds numbers and high-velocity head are concerned, the pressure drop in the forechamber, occurring during the working regime, has a destructive effect. For example, in the IT-301 installation [9], at M = 8.5, already 15 msec after the beginning of the regime, the Re numbers decrease approximately by a factor of 2 compared to the initial values. A similar situation also occurs in other installations with constant forechamber volume. Attempts to increase the starting pressures in such systems will only intensify these phenomena due to real gas effects.

The problem of the accuracy required in reproducing the Re numbers in the models is discussed seriously nowhere in the literature, but the necessary requirements for studies at Re = const exist [6, 9, 10], and they are related to the possibility of a transition from a turbulent to laminar flow past the model during a single experiment. Depending on the problems solved, the change in the Re numbers can be an obstacle to obtaining reliable data, for example, in studying the surface heating regime, operational efficiency of control surfaces, and so on, since these phenomena greatly depend on the nature of the flow in the boundary layer (turbulent or laminar).

For regimes near the boundary layer transition region, a change in the Re number by a factor of 3-5 completely changes the flow regime in the boundary layer from turbulent to laminar (see, for example, [7, 9]). In the A-1 installation, the Re numbers in the flow of the working regime remain practically unchanged. Starting from what was said above, in order to compare with other systems, we will assume that the Re numbers during a single experiment must not change by more than a factor of 2. For installations of the IT-301 [9] and Long Shot [4, 5] type, this condition greatly decreases the time of the working regime compared to those indicated in the certificates of the installations.

The situation is even more serious with the velocity head. Estimates show that during operation with a constant forechamber volume, in order to measure force actions on the model to within at least 10%, it is possible to use not more than 7% of the gas stored in the forechamber. As follows from [4, 5], the maximum pressures in the record, to this day, Long Shot system attains 400 MPa; the temperature attained 2400°K; the forechamber volume is 0.33 liter and less than 20 cm^3 flows out of the chamber under conditions when the drop in p_0 does not exceed 10%. In the small A-1 installation, at this pressure, an outflow of up to 30 cm^3 of gas in the constant regime is provided.

Calculation shows that for $M \approx 18$ the use of pressures up to 1500 MPa in the existing A-1 installation, in spite of its small dimensions, makes it possible to achieve Re numbers, scaled to the diameter of the nozzle edge, that are approximately six times higher, while the temperature in the forechamber can be decreased from 2400 to 2000°K compared to the Long Shot installation, whose dimensions exceed 28 m.

Figure 3 shows the regions of flow simulation with respect to the M and Re numbers, obtained on A-1 and other installations with pulsed action. In constructing the graphs, the diameter of the nozzle edge was taken as the characteristic dimension for determining the

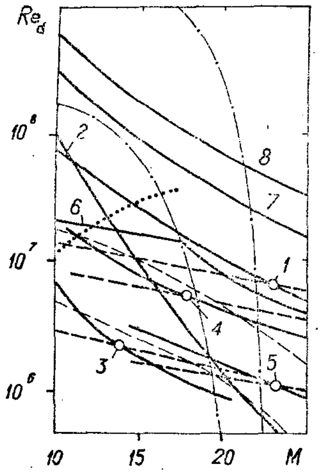

Fig. 3

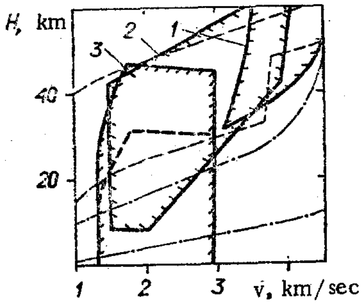

Fig. 4

Re_d numbers. For the A-1 installation, the critical section dimensions were taken so as to ensure the working regime for 15 msec. For other installations, the open circles indicate points that determine the regime of operation with a pressure drop in the forechamber by 10% over 15 msec. The decrease in the Mach numbers greatly accelerates the pressure drop. Thus, in the Long Shot type installation with M-15, this pressure drop occurs over 2 msec [4]. The overall operational time of the shock tubes (the characteristic of one of them is shown in Fig. 3) generally does not exceed several milliseconds.

The regions in Fig. 3 show the entry corridors of orbital vehicles (between the thin dashed lines), ballistic rockets (between the dot—dash lines), and the transition line of the flow into the boundary layer (dots) according to data in [6, 7, 9]; curves 1-8 indicate the boundaries of the region of simulation for different systems: 1) Hot Shot-F type installations [6, 7]; 2) the shock tube at the Cornell laboratory (CAL-96) [6, 7]; 3) IT-309 [9]; 4) the pulsed tube built by the McDonnell Company (MAC) [10, 11]; 5) the Long Shot system [3, 4, 7]; 6) the A-1 installation. The dashed lines, intersecting the curves at points, show the boundaries of the region of simulation with a pressure drop in the forechamber by 10% from the initial value over 15 msec. It is evident from Fig. 3 that in spite of the small dimensions, A-1 exceeds the existing systems according to the region of M and Re numbers simulated.

Figure 4 shows the regions of simulation in velocity—altitude flight coordinates. Here the dashed lines delineate the flight corridor of possible hypersonic vehicles [6, 7], and the dot—dash lines delineate the corridors of ballistic missiles from medium to intercontinental range [1, 6, 7]; line 1 delineates the region of simulation, provided by the Hot Shot-F type system [12], line 2 corresponds to the Cornell laboratory shock tubes [6, 7], and line 3 shows the region simulated by the A-1 type installation. The dashed line delineates the region of simulation with respect to velocity and density. In this case, A-1 covers a considerable region of high-velocity heads. From existing systems, only the large (≈30 m) CAL-96 system, which provides an operational time of not more than 6 msec, can compete.

The gasdynamic A-1 installation can be viewed as an operating model of a large wind tunnel.

It is well known that the Mach number, density, and velocity of the flow, attained on the saturation line, are determined for a given gas only by the parameters in the forechamber, while the Reynolds numbers depend also on the dimensions of the installation and the operational time. In order to compare installations with different scales with the same flow parameters on the saturation line, we shall represent the Reynolds number in the working part of the flow in the form $Re = \rho v d/\eta = 4\rho_0 V_0/\pi\eta t d$, where ρ_0 and V_0 are the density and volume of the gas in the forechamber; η is the coefficient of dynamic viscosity; t is the operating time; d is the diameter of the flow; ρ and v are the density and velocity of the gas in the working part of the nozzle. With a geometrically similar change in the dimensions of the installation (L) and retaining the flow parameters in the working part of the nozzle, the volume of the forechamber changes as L^3, the surface area of the cross section of the flow changes as L^2, while $t \sim L$. Thus $Re \sim L$.

Since the forces acting in the system from the gas and the corresponding stresses are two orders of magnitude greater than the gravitational force, the latter can be neglected for force calculations. This situation remains when the scale of the installation is increased by an order of magnitude. All stresses in the elements of the structure stem from the action of static forces from the side of the gas, inertial and shock loads. The installation is designed and constructed in such a way that the stresses on all of its elements do not exceed the limits of the elasticity zone. Evidently, the stresses caused by static loads, with a similar geometric increase in the dimensions of the installation, will remain. As dimensional analysis shows, the steady-state velocity of the elements in the system will also remain the same, from which follows the fact that the stresses, related to the shock and inertia loads, remain the same.

As far as thermal phenomena are concerned, increasing the scale will decrease the relative heat losses and the intensity of thermal shocks, since heating zones increase proportionally to $\sqrt{t}$, while the time increases linearly with increasing scale of the installation. An increase in the diameter of the critical section of the nozzle will have a favorable effect on its stability.

Thus, the possibility of greatly increasing the dimensions of installations is determined only by technological considerations. Experience in designing and building the A-1 installation shows the possibility of increasing the scale at least by a factor of 4 without using special large technological facilities for construction since the dimensions of the largest parts will not exceed 1.5 m. In this case, the Re numbers and the operational time will increase by a factor of 4.

In the case that the operational time remains in the range of 15 msec, the Re numbers can be increased by a factor of 8, while the dynamic loads, although they increase, nevertheless remain within a permissible range. However, in connection with the increase of the mutual velocity of elements in the structure of the automatic precompression system, additional work may be necessary on the sealing system for the forechamber.

Figure 3 shows the boundaries of the simulated region for systems of the A-1 type increased in scale by a factor of 4 for operational times of 60 and 15 msec (curves 7 and 8, respectively).

It is evident that for such dimensions of the installation, it is possible to simulate natural flow, with respect to M and Re numbers, for practically all problems of modern hypersonic aerodynamics. The use of air as a working gas opens up possibilities for studying flows in models of a hypersonic flow-through thermojet together with an air intake.

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INFLUENCE OF THE SHAPE OF THE SUPERSONIC PART OF A NOZZLE ON THE RATE OF REDISTRIBUTION OF MOLECULES OVER VIBRATIONAL LEVELS IN THE ACTIVE MEDIUM OF A CO GASDYNAMIC LASER

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In the majority of experimental reports devoted to the study of CO gasdynamic lasers (GDL) [1-5] conical nozzles having expansion half-angles of 7.5-12° in the supersonic part have been used, and in these reports the resonator was at a considerable distance (0.5-1 m) from the critical cross section of the nozzle. In [6, 7], however, the possibility of creating CO GDL with shorter nozzles was determined experimentally (expansion half-angle 26°, distance from nozzle critical cross section to resonator axis 0.065 m). Theoretical investigations made in [8-11] showed that the process of vibrational relaxation in the active medium of a CO gasdynamic laser can be divided into two regions. The most intense deactivation of vibrational energy takes place in the first region (near the nozzle critical cross section at a high temperature and high pressure), while in the second region (at low pressures and temperatures) the vibrational—translational deactivation is slowed, since the process of redistribution of molecules over vibrational levels is primary. To assure the efficient "freezing in" of vibrational energy, the gas must be transferred from the first region to the second in the shortest time, i.e., in the first region the minimum nozzle diameter and the maximum possible expansion angle are required. The question of what the nozzle profile in the second region should be to assure that the maximum value of the optical amplification factor of the active medium is achieved at the minimum distance from the nozzle critical cross section has not been studied. The results of calculated investigations of the process of vibrational relaxation of carbon monoxide molecules in supersonic streams with different expansion geometries are given in the present report.

We consider the steady, quasi-one-dimensional, adiabatic flow of a CO—Ar mixture in a plane supersonic nozzle with a given configuration along the x axis. It is assumed that only one-quantum transitions take part in the relaxation processes and that local equilibrium between the translational and rotational degrees of freedom exists at each point of the stream. Equilibrium over all degrees of freedom is assumed in the nozzle critical cross section. Within the framework of the enumerated assumptions, the equations of kinetics of vibrational relaxation are written in the form

$$u\frac{dC_v}{dx} = K_{v+1,v}C_{v+1}N - (K_{v,v-1} + K_{v,v+1})C_vN + \tag{1}$$

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