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EXPERIMENTAL INVESTIGATION OF SUPERSONIC FLOW ABOUT AN OBSTACLE WITH POWER DELIVERY INTO THE UNDISTURBED FLOW

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A technique and results of experimental investigation of supersonic flow about bodies with optical breakdown in the windstream are presented. Flow parameter evolution when pulsed power is delivered locally is tracked. Experimental and calculated flow patterns are compared.

In recent years substantial interest has been expressed in problems of supersonic flow about bodies in the presence of a nonuniform gasdynamic parameter distribution in the windstream, produced by local power delivery or other causes [1-7]. An energetic effect on the windstream was assumed to be able to change substantially the regimes of flow about bodies situated in the wake of the power delivery region.

Investigations performed in this field to date have been carried out mainly using various methods of mathematical modeling [1-5]. An exception is the experimental works [6, 7], where a gasdynamic parameter nonuniformity in the windstream was produced by various methods (using electrodes, a hot wire, a wing tip vortex, axial or radial injection of a foreign gas, etc.).

The experimental setup developed makes it possible to affect energetically the windstream using optical breakdown of air by focused radiation of a pulsed solid-state laser without introducing any devices into the flow.

Description of the Experimental Setup. A schematic overview of the experimental setup is given in Fig. 1. Experiments were performed using an ST-2 wind tunnel at various Mach numbers of the flow. The wind tunnel has an open operating part of round cross section with a diameter of 100 mm. A GOS-1001 pulsed solid-state laser working in the mode of *Q*-modulation was used as a source of laser radiation. The laser was provided with an optical gate made of specially processed LiF crystal, which made it possible to produce a series of approximately 150-nsec pulses. The energy and number of the pulses were changed by changing the GOS-1001 capacitor charge voltage, which changed the pumping energy of the active element of the laser. An optical focusing scheme with a 100-mm focal length made it possible to provide in a given region a laser radiation intensity higher than the optical breakdown threshold of air both in a stationary gas and under the conditions of the ST-2 wind tunnel working area. Thus, upon operation of the GOS-1001 laser optical breakdown of air took place at a given point of the supersonic flow or in stationary gas, and a laser spark developed, which provided power delivery into the gas. The emission intensity and duration of the laser spark were recorded with a high-speed photodiode and displayed on the screen of an S8-13 storage oscilloscope.

We used a schlieren-shadow device combined with a VFU-1 high-speed photocamera to investigate visually development processes of the power delivery region with a characteristic duration of 10^{-5}– 10^{-3} sec in stationary air and a supersonic flow as well as to study the influence of gasdynamic parameter distribution nonuniformity, caused by optical breakdown in the supersonic flow, on the flow about an obstacle. In the experiments the illuminator of the schlieren-shadow device worked in the pulsed mode and was activated by a signal from the VFU-1 control panel simultaneously with the start of image development on the photofilm. The VFU-1 camera worked in the time loop mode with two-row inset. Exposure of 49 frames took 0.5 msec. The IFK-50 pulsed lamp of the illuminator had a 3×20-mm discharge column so that with a large reserve its image covered the diaphragm of the

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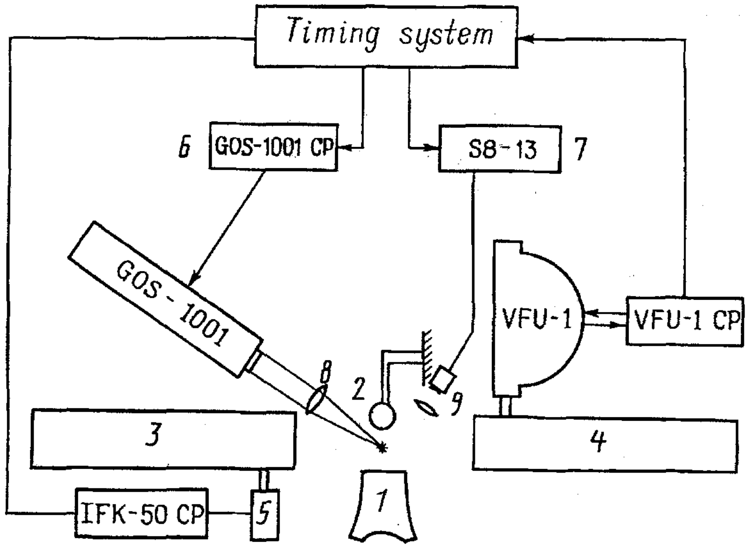

Fig. 1. Scheme of the experimental setup: 1) the nozzle of the supersonic wind tunnel; 2) the body (sphere); 3, 4) the illuminating and detecting parts of the schlieren-shadow device, respectively; 5) the IFK-50 illuminating lamp; 6) the control panel (CP) of the GOS-1001 pulsed laser; 7) the S8-13 storage oscilloscope; 8) the objective that focuses the laser emission; 9) the high-speed photodiode with the focusing lens, detecting the light flux.

schlieren-shadow device. The supply voltage of the IFK-50 lamp was 1000 V, and the capacity of the discharge capacitor was 1000 μF. The duration of the flash was of the order of 1 msec.

The timing system of the experimental setup provided simultaneous operation of the GOS-1001 laser, the illuminator lamp of the schlieren-shadow device, and the S8-13 storage oscilloscope by the driving pulse from the VFU-1.

Experimental Technique. The experimental investigations were performed in several stages. In the first stage propagation of disturbances from a single laser spark in stationary air was investigated. The main problem to be solved at this stage was to establish the applicability of point explosion theory for approximate evaluation of the energy delivered to the air through a laser spark. For this purpose the propagation velocity of disturbances from the optical breakdown region in stationary air was calculated from experimental photographs with a known rate of photorecording. Then, on the basis of this velocity the energy delivered to the air was calculated and the results obtained were compared with those of investigations conducted previously.

In the second stage the propagation of disturbances from a single laser spark was investigated in a supersonic flow, and the evolution of the hot region was also studied.

The main purpose of the investigations in the third stage was to determine characteristic properties of the interaction of disturbances, introduced by a single laser spark into a supersonic flow with the bow shock wave upstream of a spherical obstacle.

In the fourth stage we studied the possibility of producing a long rarefied hot channel in a supersonic flow using a series of laser pulses. Additionally, under these conditions we investigated the flow about a spherical obstacle and the possibility of obtaining stationary flows with pulsed energy delivery into the flow.

Discussion of the Experimental Results. Based on experimental photographs an analysis of the character and velocity of propagation of disturbance from the optical breakdown region in stationary air (Fig. 2a) enabled us to conclude the following. The front of disturbances propagating from a laser spark is nearly spherical in shape, which allows us to conclude that the theory of a point explosion can be used for calculating the energy delivered to the air through optical breakdown of it. The velocity of disturbance propagation calculated for the time of completion of hot region emission was 474 m/sec. This value is substantially higher than the velocity of sound in air. Hence, we can conclude that disturbances propagating from the region of optical breakdown are a shock wave

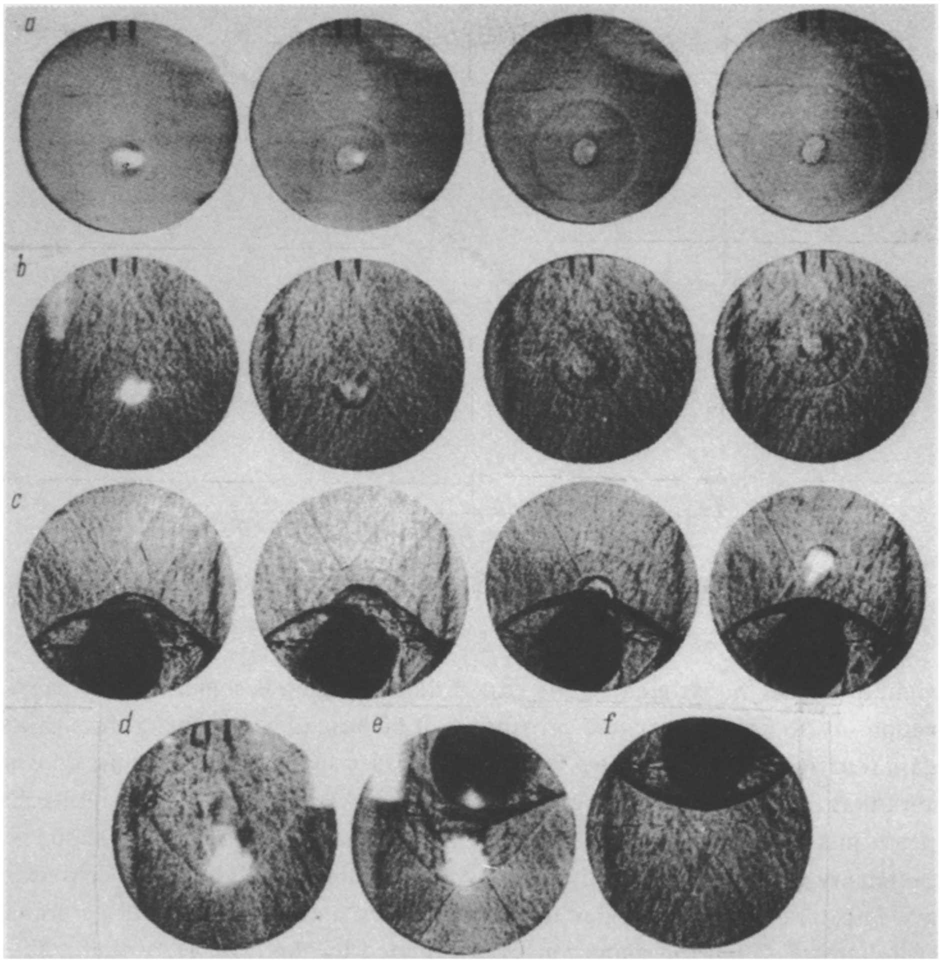

Fig. 2. Selected shadow photographs of the processes of energy delivery into the supersonic flow (the interval between frames is 20 μsec): a) pulsed energy delivery into the stationary gas (10-mm scale marks are shown at the top); b) pulsed power delivery into the free supersonic jet, $M_\infty = 1.95$; c) the supersonic flow about the sphere with pulsed power delivery into the undisturbed flow; d, e) the flow patterns when power is delivered by a series of pulses with an interval of 200 μsec into the free and obstructed flow, respectively; f) the undisturbed supersonic flow about the sphere.

(SW). With increase in the distance between the focus and the front of the SW the velocity of the front decreases rapidly and tends to the velocity of sound in the medium (Fig. 3).

The value of the energy E delivered to the air in a single laser pulse was calculated by Sedov's formula [8, 9]:

$$R = \xi_0 \left[\frac{E}{\varphi_0}\right]^{0.2} \tau^{0.4} .$$

The value of the energy delivered to the air calculated by the above formula for the time $\tau = 2.5 \cdot 10^{-5}$ sec, when the shock wave front radius is $R = 1.4 \cdot 10^{-3}$ m for the air density $\rho_0 = 1.21$ kg/m^3 and the factor $\xi = 1.033$ [8], was 0.95 J, which agrees with the value of E in a pulse of the employed laser with the optical gate.

The photographs presented show that the size of the power delivery region is practically unchanged after the end of emission from the region (t ≈ 30-40 μsec). This means that the values of the pressure in the hot region

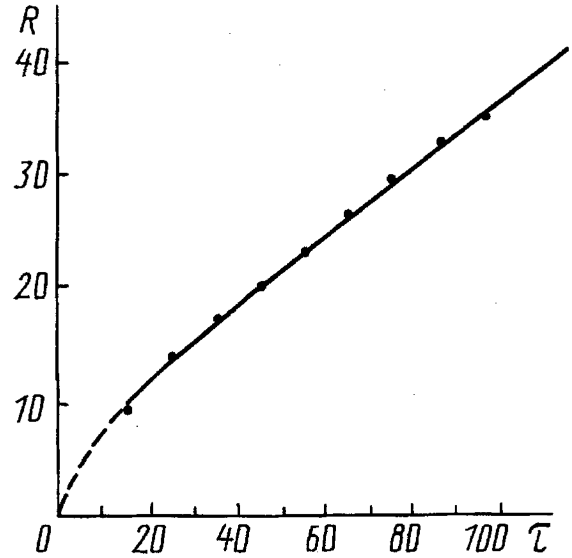

Fig. 3. Radius of the shock wave in the stationary gas as a function of time. R, mm; τ, μsec.

and in the environment are equal. Subsequently, the size of the hot region is somewhat decreases with time, which is caused by a reduction in the temperature and pressure in it because of heat transfer through its boundary [8].

The propagation pattern of a shock wave from a single laser spark in a supersonic flow is given in Fig. 2b. The photograph shows that initially the heating of the gas in the power delivery region and its dispersal caused by thermal expansion lead, just as in the previous case, to formation of a shock wave whose shape is close to spherical initially and whose intensity is rather high windward only and is substantially reduced behind the hot gas region. The shock wave travels upstream from the region of power delivery until the velocity of its propagation is equal to the velocity of the windstream. Then the disturbances are carried by the flow. Here the drift velocity of the hot region of 520 m/sec, calculated from the photographs, corresponds to the flow velocity in the working part of the wind tunnel when $M_\infty = 1.95$.

The presence of a spherical body in the flow with optical breakdown of the undisturbed flow ahead of it (Fig. 2c) leads to formation of a more complex shock-wave structure. Interaction of the shock wave formed upon optical breakdown of the flow and the bow SW ahead of the obstacle (sphere) affected negligibly the shape of the former because the intensity of the shock wave traveling from the power delivery region is substantially lower than the intensity of the bow shock wave. The photographs show that the bow shock wave ahead the sphere started to transform upon interaction directly with the hot region itself rather than with the shock wave from the breakdown. When the hot gas interacted with the bow shock wave, the axial part of the wave was deformed and started to travel upstream in the rarefied hot channel. The case of power delivery shown in the photographs was asymmetric relative to the axes of the flow and the sphere, which caused asymmetry of the whole shock-wave structure. Then the formed shock-wave structure decayed and the classical pattern of supersonic flow about a sphere was formed (Fig. 2f).

The character of hot region evolution revealed in the investigation of the energetic effect on the windstream by a single pulse, allows us to assume that a long rarefied hot channel can be produced by a series of pulse for studying stationary flow modes. The experiments on interaction of a series of laser sparks of various frequencies with the supersonic flow showed that, to support a stationary shock wave ahead of the power delivery region, power should be delivered with a delay that allows the disturbances from the power delivery region to reach the shock wave before the beginning of downstream drift of the SW (in this case it should be taken into account that the velocity of disturbance propagation in a heated gas is substantially higher). This flow pattern was observed when power was delivered in intervals of $t = 0.2$ msec (Fig. 2d), which allows us to conclude that a quasistationary flow pattern can be produced by using pulsed power delivery into the gas flow. As a result of the periodic pulsed effect of laser radiation a shock wave structure was formed (Fig. 2d) that consisted of the power delivery region, the hot

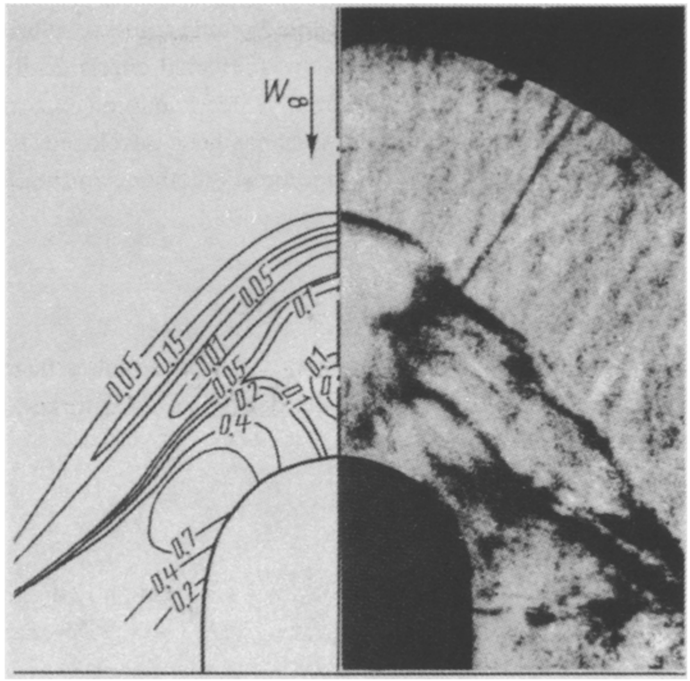

Fig. 4. Comparison of calculated pressure isolines with results of the optical experiment (the nose part has spherical blunting with a diameter of 30 mm; $M_\infty = 1.95$; the gap between the body and the breakdown is 22 mm; power is delivered in pulses with a pulse length of ≈150 nsec and a pulse energy of ≈ 1.5 J; the time $\tau = 0.3$ msec after the start of breakdown).

gas column established behind it, and the shock wave ahead of it. The shock wave was spherical near the axis and gave way to a cone with a half-opening angle that depends on the energy in the laser pulse and the Mach number M_∞ of the windstream.

When the spherical body was introduced into the flow as an obstacle (Fig. 2e), the shock-wave structure was substantially influenced by the magnitude of the energy in the pulse, the pulse repetition frequency, and the disposition of the power delivery region relative to the body.

The short duration of the quasistationary mode in the experiment and the related requirements on the recording apparatus greatly hinder obtaining systematic quantitative data on the processes under investigation. The only possibility of obtaining such results is by visually representing and photographing the flow structures. On the other hand, numerical investigation of the flows with power delivery to the windstream that takes into account radiation effects and properties of a real gas is a rather complicated problem as regards algorithmization and implementation of the calculation. At the same time an analysis of the gasdynamic phenomena occurring under the conditions of the experiment described above and experience in calculating similar problems allow us to use a simpler mathematical model and implement an algorithm based on S. K. Godunov's finite-difference method of first-order accuracy for nonstationary problems.

The initial system of equations was closed by the ideal gas equation of state. Power delivery was simulated by an additional term in the energy equation. Uniqueness conditions for the spatial coordinate, the time, and the delivered power were determined in correspondence with parameters of the experiment. In this case the density of the delivered power in the power delivery region was constant during the pulse.

The calculation was performed for the case of axisymmetric flow about a cylindrical model with spherical blunting. Fields of gasdynamic parameters were constructed for times corresponding to those of the experimental photographs of the flow patterns. A comparison of calculated pressure isolines with flow patterns obtained in the experiment indicates satisfactory agreement between them (Fig. 4). This allows us to conclude that the numerical investigation yields information on the influence of power delivery on head resistance and on redistribution of gasdynamic parameters that is valid and reflects accurately the dynamics and regularities of the processes taking place when the undisturbed supersonic flow ahead the obstacle is affected energetically.

In conclusion the following main results can be noted. A technique of experimental investigation of the influence of local power delivery on supersonic flow about bodies has been developed. Experimental data have been compared with results of a calculation performed by S. K. Godunov's method, and the comparison has shown that they were in good agreement.

NOTATION

R, the current value of the shock wave front radius; ξ_0, a proportionality factor; E, the energy delivered to the air; τ, the time from the start of power delivery; ρ_0, the density of undisturbed air; M_∞, the Mach number of the undisturbed flow; t, the time interval between pulses.

REFERENCES

1. I. A. Belov, Interaction of Nonuniform Flows with Obstacles [in Russian], Leningrad (1983).
2. V. I. Artem'ev, V. I. Bergel'son, A. A. Kalmykov, et al., Izv. Akad. Nauk SSSR, Ser. Mekh. Zhid. Gaza, No. 2, 158-163 (1988).
3. V. I. Artem'ev, V. I. Bergel'son, I. V. Nemchinov, et al., Izv. Akad. Nauk SSSR, Ser. Mekh. Zhid. Gaza, No. 5, 146-151 (1989).
4. P. Yu. Georgievskii and V. A. Levin, Pis'ma Zh. Tekh. Fiz., **14**, No. 8, 684-687 (1988).
5. V. Yu. Borzov, I. V. Rybka, and A. S. Yur'ev, Inzh.-Fiz. Zh., **62**, No. 2, 243-247 (1992).
6. V. V. Vitkovskii, L. P. Grachev, N. N. Gritsov, et al., Teplofiz. Vys. Temp., **28**, No. 26, 1156-1163 (1990).
7. G. F. Glotov, Uch. Zap. TsAGI, **20**, No. 5, 21-33 (1989).
8. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Moscow, (1966).
9. B. N. Chetverushkin, Mathematical Modeling of Problems of Radiating Gas Dynamics [in Russian], Moscow (1985).