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EXPERIMENTAL STUDY OF THE REVERSE FLOW IN THE FORWARD SEPARATION REGION IN A PULSATING FLOW AROUND A SPIKED BODY

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The flow with a free-stream Mach number $M_\infty = 6$ *around a cylindrical body with a sharp spike is studied. The existence of a supersonic reverse flow for one of the phases of the pulsating flow regime is experimentally validated. A range of spike lengths is determined, which ensures a region of a supersonic reverse flow near the side surface of the spike. The time of existence of the supersonic reverse flow region is shown to be 0.15 of the period of pulsations if the spike length equals the model diameter.*

Key words: *supersonic flow, shock waves, self-sustained pulsations.*

Introduction. A supersonic gas flow around a spiked blunt body is accompanied by the emergence of a flow with a forward separation region. At certain geometric and gas-dynamic parameters, there arises a periodic self-oscillatory flow. Two types of such a flow are distinguished, depending on the spike length. In the oscillatory flow regime, the conical shock wave bounding the separation region performs small periodic transverse oscillations. The shape of the wave remains essentially unchanged. Figures 1a and 1b show the flow structures for two typical phases of oscillations.

As the spike length is reduced, the amplitude of oscillations increases, and a certain value of the amplitude gives rise to the pulsating flow regime. At this moment, the shape of the separation region becomes essentially different. Typical structures of the flow for two phases are shown in Figs. 1c and 1d. As the pulsating process evolves, the volume of the separation region increases, the conical wave transforms to a hemispherical one, and then the separation region disappears because the flow rate of the gas escaping from the separation region is significantly greater than the flow rate of the incoming gas. After this phase of pulsations is completed, a new separation zone bounded by a conical shock wave appears, and the entire process is periodically repeated. Such a flow regime, which was first discovered by Mair (see [1]), is considered in the present paper.

This problem has been studied in many experimental and theoretical investigations (see, e.g., [2–6]). The physical pattern of such a flow, however, has not been adequately addressed, which necessitates further research.

According to [4, 6], the main reason for origination of a pulsating flow regime is the formation of an annular supersonic jet J (Fig. 1c) at the point T of intersection of the conical shock wave W_c and the bow shock wave W_1. The mechanism responsible for the emergence of a pulsating flow is as follows. A high-velocity gas flow behind a weak shock wave W_c moves in the form of an annular jet J in the region between this wave and the separation-region boundary toward the body on which this flow is impinging. Because of jet curving toward the model centerline, the gas predominantly enters the separation region. The size of this region increases, which converts the conical shock wave W_c into the detached curved shock wave W_1. At a certain stage of development of the pulsating process, the increase in the radial size of the separation region makes the diameter of the annular jet J greater than the cylinder diameter D. The incoming flow ceases to add the high-pressure gas into the separation region, and the pressure in the separation region decreases. As a result, the bow shock wave W_1 is attenuated and entrained downstream.

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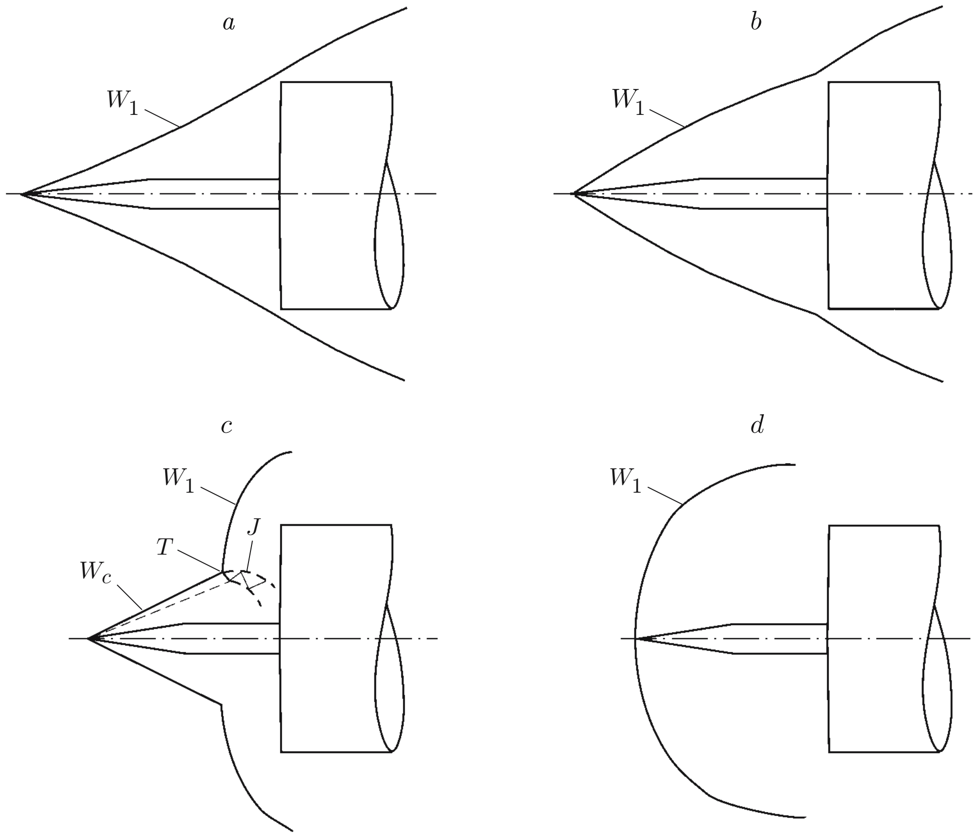

Fig. 1. Oscillatory (a and b) and pulsating (c and d) flow regimes.

Another weak shock W_c arises again near the spike tip subjected to a supersonic gas flow, and conditions for formation of a new separation region are created. The mechanism of mass-flow oscillations is described in more detail for a free-stream Mach number $M_\infty = 2$ in [4].

It was believed before now that gas viscosity exerts a significant effect on the characteristics of an unsteady pulsating process. Such a flow could be obtained only by solving the Navier–Stokes equations (see, e.g., [3]). Babarykin et al. [5], however, proved that this problem could be solved by the Euler equations. Moreover, some specific features of the process evolution, which had not been described in previous publications, were discovered in [5]. In particular, the possibility of existence of a supersonic flow in the forward separation region was noted.

The objective of the present work is to refine the physical features of flow pulsations in high-velocity supersonic flows and to compare these features with available mechanisms of pulsations corresponding to moderate supersonic velocities.

Experimental Equipment and System of Flow Visualization. The experiment was performed in a T-326 hypersonic wind tunnel of the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences (Fig. 2a). The nozzle-exit diameter was 200 mm.

The model to be tested was a spiked cylinder (Fig. 2b). The cylinder diameter was $D = 50$ mm, the spike length was $L = 50$ mm, the spike diameter was $d = 8$ mm, and the cone half-angle of the spike tip was $\varphi = 10°$. A gauge for measuring pressure pulsations was flush-mounted on the frontal face of the cylinder at a distance $h = 0.8R = 20$ mm ($R = D/2$) from the cylinder centerline.

The free-stream Mach number was $M_\infty = 6.08$. The pressure in the settling chamber was $9.81 \cdot 10^5$ Pa, the temperature in the settling chamber was 110°C, the dynamic pressure was $q = 15 \cdot 10^3$ Pa, and the Reynolds number per meter was $\mathrm{Re}_1 = 1.27 \cdot 10^7$ m^{-1}.

The schlieren pictures of the flow were taken by an IAB-451 shadowgraph. A source of light was placed onto the collimator part of the instrument, and a CCD camera was located on the detector part. The pictures were

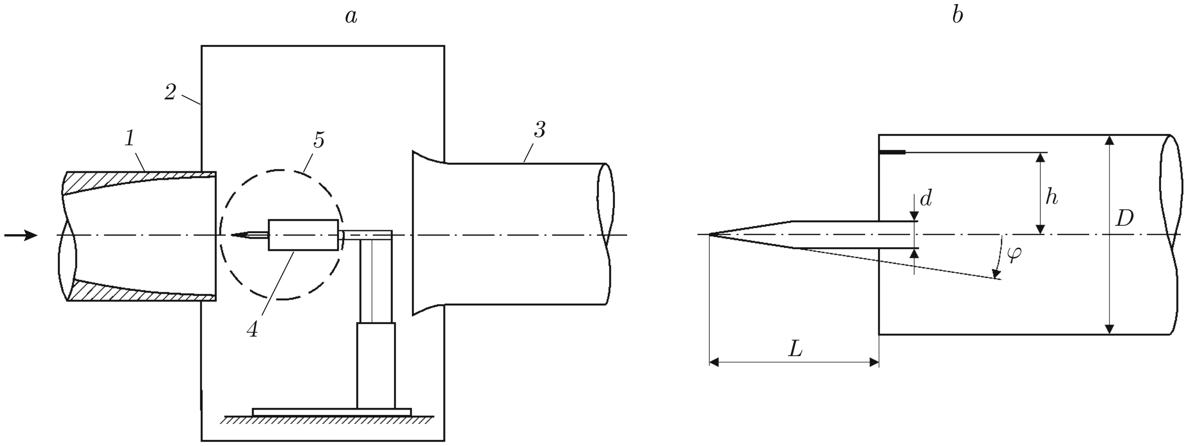

Fig. 2. Sketch of the test facility (a) and geometric parameters of the model (b): 1) wind-tunnel nozzle; 2) test section; 3) diffuser; 4) model to be tested; 5) window for flow visualization.

taken with a frequency 30 frames per second. A straight sheet in the vertical position was used. The exposure time was determined by the duration of the light pulse and amounted to 2 μsec.

A piezoresistor gauge of pressure pulsations was used in the experiment. The range of measurements was -100 to 60 kPa, and the frequency range was 0 to 100 kHz. The outer diameter of the gauge was 3.3 mm.

In addition to experiments with the model described above, we also performed experiments under the same conditions with a spike length $27.5 \leqslant L \leqslant 72.5$ mm. The flow character remained essentially unchanged in this range of spike lengths. At $L > 72.5$ mm, the pulsating flow regime transformed to the oscillatory mode. At spike lengths $L < 27.5$ mm, the flow character was not studied. In further discussions, the experimental data are presented for $L/D = 1$, if not indicated otherwise.

Technique of Registration of Self-Sustained Pulsations in Time. In the course of the experiment, we simultaneously recorded the values measured by the pressure gauge (mounted at a distance $h = 0.8R$ from the model centerline) and the time instants when the instantaneous schlieren pictures were taken. As the process under study is quasi-periodic, we could obtain a sequence of photographs illustrating one cycle of self-sustained pulsations, using the parameter $\tau = (t - t_0)/T_a$. For this purpose, we calculated the relative time of obtaining each photograph $\tau_f = (t_f - t_0)/T_a$ (t is the time, $T_a = t_1 - t_0$, where t_0 and t_1 are the times of the beginning and end of the cycle of self-sustained pulsations, and t_f is the time when the photograph was taken). Thus, the condition $t_0 \leqslant t \leqslant t_1$ is described by the inequality $0 \leqslant \tau \leqslant 1$. The beginning ($\tau = 0$) of the cycle of self-sustained pulsations is assumed to be the time when the bow shock wave is located near the spike tip (see Fig. 1d). The equipment and the technique used to construct the sequence of photographs were described in more detail in [7].

For the geometric and gas-dynamic parameters of the experiment used, the mean period of the cycle of self-sustained pulsations is $T_m = 334$ μsec. The root-mean-square deviation from the mean value of the period is $T_\Sigma = 2.08\%$.

Figure 3 shows a cycle of self-sustained pulsations and the averaged oscillogram of pressure fluctuations on the frontal face of the cylinder, which was registered by the pressure gauge. The points on the oscillogram correspond to times when the displayed photographs were taken. At $\mathrm{M}_\infty = 6$, the mechanism of self-sustained pulsations observed is consistent with the mechanism of self-sustained pulsations at $\mathrm{M}_\infty = 2$ [4]. The photographs corresponding to the time interval $0 \leqslant \tau \leqslant 0.4$ show the motion of the bow shock wave W_1 toward the frontal face of the cylinder. A conical shock wave W_c is formed on the spike tip, with a forward separation region behind this wave. The time interval $0.4 \leqslant \tau \leqslant 1.0$ covers the development of the separation zone, its subsequent emptying, and formation of a new bow shock wave at the spike tip. The first maximum in the oscillogram corresponds to the moment when the shock wave W_1 approaches the frontal face of the cylinder, and the second maximum refers to the moment when the high-pressure annular jet J passes near the pressure gauge, as the separation region expands.

Research Results. One of the little-studied features of the pulsating flow regime is the presence of a local supersonic reverse flow region near the side surface of a sharp spike.

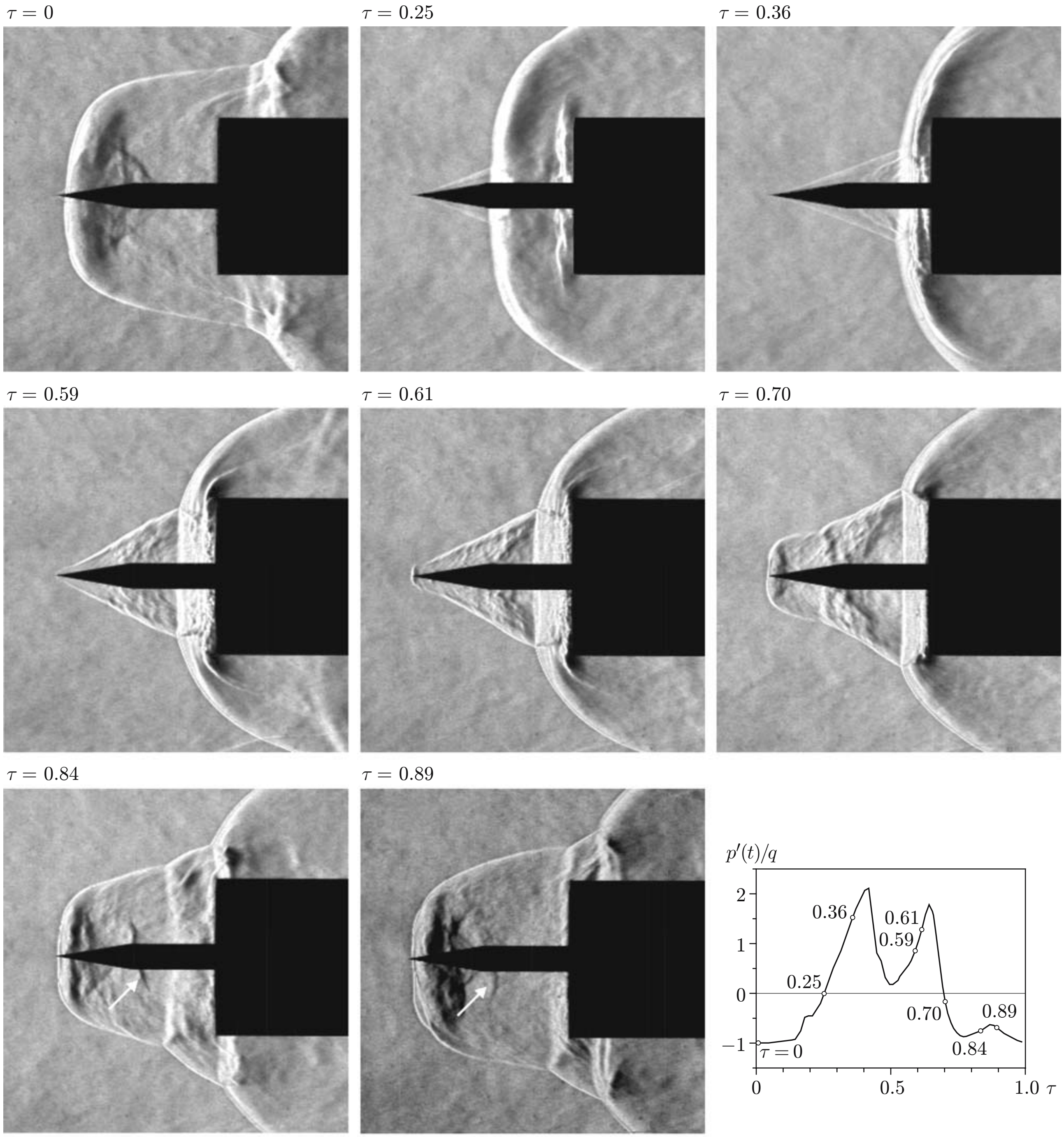

Fig. 3. Cycle of self-sustained pulsations in the time interval $0 \leqslant \tau \leqslant 1$ and oscillogram of pressure fluctuations.

Let us consider the possibility of existence of such a flow. At the time $\tau = 0.64$, the pressure gauge registers the second maximum of pressure $p_1 = 52$ kPa (see Fig. 3). According to [8], this maximum is caused by a supersonic high-pressure annular jet passing near the gauge; the existence of this jet was established in [4, 6]. When the jet becomes decelerated on the frontal face of the cylinder, an annular zone with elevated near-wall pressure is formed on the surface of the frontal face of the cylinder. As the radial size of the separation region increases, this zone expands, and a local pressure maximum appears on the oscillogram. It should be noted that there is a significant difference in pressure at this moment inside the separation region between the zone near the frontal face of the cylinder and the zone near the spike tip.

Let us estimate the velocity of the reverse flow induced by this pressure difference. Let the maximum value of the total pressure in the annular jet in the time interval $0.4 \leqslant \tau \leqslant 0.7$ (time of increasing of the radial size of the separation region from the moment the bow shock approaches the frontal face of the cylinder to the moment of separation-region emptying) be approximately constant. As the jet becomes decelerated on the frontal face of the cylinder, the static pressure near the cylinder surface becomes equal to the near-wall pressure recorded by the gauge and reaches $p_1 = 52$ kPa. The flow velocity near the frontal face of the cylinder equals zero, and the temperature equals the temperature in the settling chamber (393 K).

Let the pressure inside the separation region at the initial time ($\tau = 0.4$) be equal to the pressure behind the conical shock wave near the spike tip with an angle of inclination to the axis $\beta = 19°$ ($p_2 = 3$ kPa), the temperature be equal to the temperature behind the conical wave (82 K), and the flow velocity be zero.

Thus, there is a discontinuity in flow parameters near the frontal face of the cylinder and the spike tip at the initial time. This discontinuity is unstable and decomposes into a shock wave moving toward the spike tip and an expansion wave moving toward the frontal face of the cylinder. Solving the problem of discontinuity decay in a one-dimensional formulation (paper [9] was involved) implies that the velocity of shock-wave motion is 425 m/sec and the velocity of the gas behind the shock wave is 290 m/sec. The Mach number is $\mathrm{M} = 1.14$ for the gas between the shock wave and the contact discontinuity separating the shock and expansion waves and $\mathrm{M} = 0.85$ for the gas between the contact discontinuity and the tail of the expansion wave.

When the gas flow reaches the spike tip, a curved shock wave is formed near the latter; the shape of this wave is close to planar. We assume that the flow inside the separation region will become steady in the next phase of the cycle of self-sustained pulsations. The gas parameters near the frontal face of the cylinder remain constant, and the pressure near the spike tip corresponds to the pressure behind the normal shock wave ($p_2 = 26.8$ kPa). Then, the flow Mach number near the spike tip, calculated by the formula for a one-dimensional steady isentropic flow (in the indicated time interval $0.4 < \tau \leqslant 0.7$) is $\mathrm{M}_2 = 1.02$. As the resultant Mach number is close to unity, such an estimate admits a time interval where a local supersonic reverse flow region near the side surface of the spike can exist.

The photographs that refer to the time interval $0.76 \leqslant \tau \leqslant 0.91$ (see Fig. 3) display a narrow dark region near the inflection where the conical part of the spike transforms to the cylindrical part (marked by an arrow). As the dark and light areas in the schlieren pictures correspond to an increase and decrease in density, respectively, in the direction from left to right, the region observed is either an expansion wave if the gas moves from the spike tip toward the frontal face of the cylinder or a compression wave (shock wave) if the gas moves upstream from the frontal face of the cylinder.

Let us consider the time evolution of self-sustained pulsations. The origin ($\tau = 0$) is assumed to be the phase of pulsations corresponding to the minimum pressure at the frontal face of the cylinder (see the oscillogram of pressure fluctuations in Fig. 3). As the bow shock wave W_1 moves toward the frontal face of the cylinder, a conical shock wave W_c is formed near the spike tip; the angle between the wave and the axis varies from $\beta = 38°$ ($\tau = 0.01$) to $\beta = 19°$ ($\tau = 0.39$). For a non-separated flow around a cone with an apex half-angle $\varphi = 10°$, the angle of inclination of the attached conical wave should be $\beta_c = 14.5°$. As $\beta > \beta_c$ for $0 \leqslant \tau \leqslant 0.4$, there is a separation region Z near the spike tip during this time interval. The flow structure near the spike tip with the bow shock wave W_1 moving toward the frontal face of the cylinder is shown in the schlieren picture ($\tau = 0.25$) corresponding to this phase of process evolution (Fig. 4a). At the time $\tau = 0.25$, the value $\beta = 20.5°$ corresponds to the flow around the cone with $\varphi = 16.5°$ without separation. The schlieren picture has a dark line (marked by an arrow) between the conical wave W_c and the spike surface; the angle of wave inclination to the axis is $\varphi_c = 16°$. This line corresponds to the mixing layer between the boundary layer separated from the spike tip and the reverse

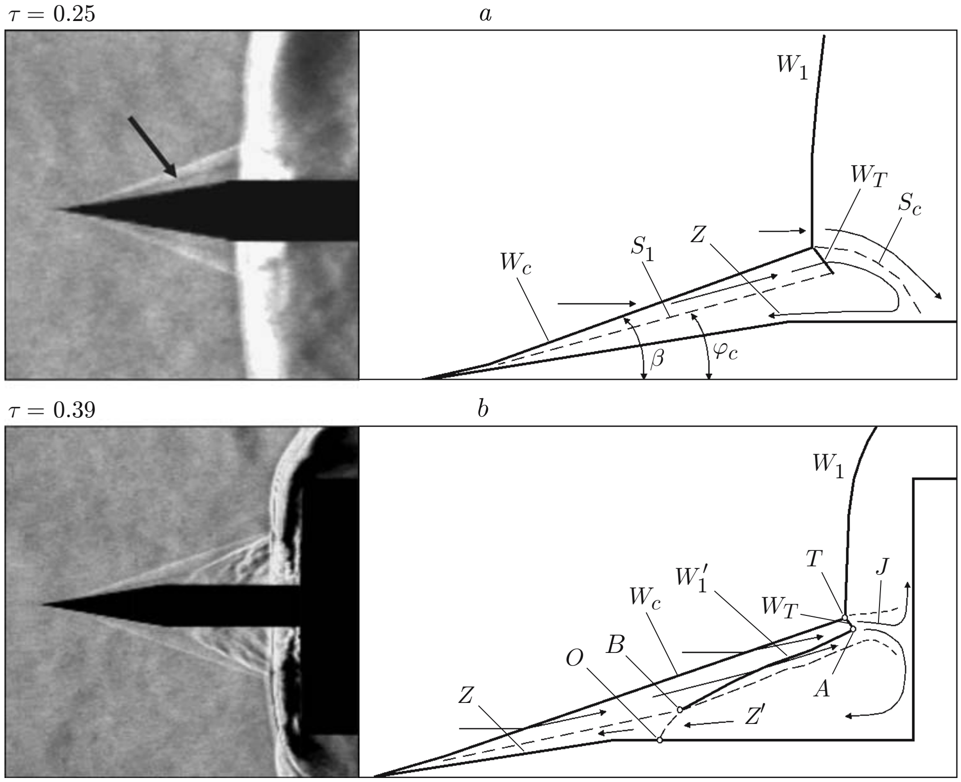

Fig. 4. Schlieren pictures and corresponding simplified patterns of the flow: (a) phase of formation of the separation region ($0 \leqslant \tau \leqslant 0.34$); (b) phase of separation-region filling by a strongly turbulized gas flow ($0.34 \leqslant \tau \leqslant 0.59$), W_1 is the bow shock wave, W_c is the conical shock wave, W_T is the shock wave forming a triple configuration together with the waves W_1 and W_c, T is the triple point (resulting from interaction of the shock waves W_1, W_c, and W_T), W_1' is the wave bounding the zone Z', AB is the segment where the wave W_1' is a shock wave and BO is the segment where the wave W_1' is a compression wave, S_1 is the mixing layer, S_c is the contact surface between the gas flow behind the wave W_T and the gas flow behind the wave W_1, J is the annular jet, Z is the separation zone behind the conical shock wave W_c, Z' is the zone of a strongly turbulized gas, β is the angle between the conical shock wave W_c and the spike centerline, and φ_c is the angle between the mixing layer S_1 and the spike centerline.

flow region near the spike surface. The flow pattern shows the mixing layer S_1 dividing two regions of the gas flow in the zone Z (the region of the separated flow behind the conical shock wave W_c and the reverse flow region near the spike surface), the shock waves W_1, W_c, and W_T, which form a triple configuration, and the contact surface S_c between the gas flow behind the shock wave W_T and the gas flow behind the wave W_1. Thus, the flow near the side surface of the spike at this time interval is directed from the frontal face of the cylinder toward the spike tip.

Figure 4b shows the flow pattern corresponding to the phase $0.34 \leqslant \tau \leqslant 0.59$ of the cycle of self-sustained pulsations. When the wave W_1 approaches the frontal face of the cylinder, an annular high-enthalpy supersonic gas jet J is formed near the line of intersection of the waves W_1 and W_c; this jet is an unsteady axisymmetric analog of interaction of shock waves of the fourth type in Edney's classification [6]. The possibility of formation of such a flow structure at $\mathrm{M}_\infty = 6$ was first demonstrated in [6]. This assumption was validated experimentally in [6, 8]. The jet J impinges onto the frontal face of the cylinder; some part of the gas flow passes outward, while the other part of the gas flow penetrates into the zone Z and forms the zone Z' of a strongly turbulized flow (the so-called gas plug), which is clearly visible in the photograph taken at the time $\tau = 0.39$. As the gas plug Z' moves toward the spike tip, the wave W_1' is formed ahead of the gas plug; this wave may be considered as consisting of two segments: AB and BO. On the segment AB, the wave W_1' is a shock wave, because the supersonic gas flow ahead of the front of this wave moves toward the turbulized gas flow "reflected" from the frontal face of the cylinder. On the segment BO, the wave W_1' is a compression wave (the gas from the zone Z' catches up with the gas from the

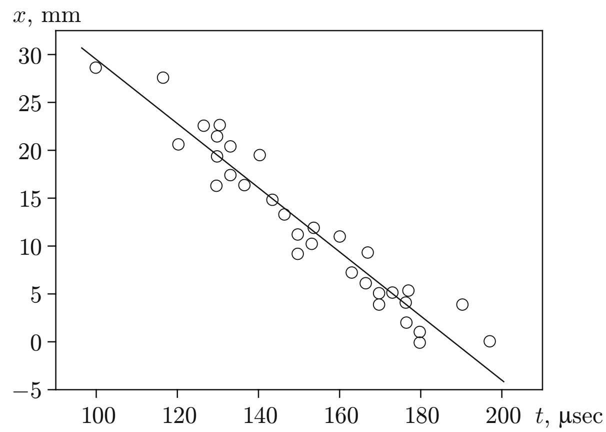

Fig. 5. Position of the contact point O of the wave W_1' and the side surface of the spike with respect to the spike tip at different times.

zone Z). The wave W_1' moves from the frontal end of the cylinder toward the spike tip, and the zone Z' gradually displaces the zone Z. At the time $\tau = 0.59$, the wave W_1' reaches the spike tip, the zone Z' completely displaces the zone Z, and the wave W_c transforms to the wave W_1'.

Figure 5 shows the position of the point O, which is the contact point of the frontal surface of the high-pressure gas plug (i.e., contact point of the wave W_1') and the side surface of the spike at different times. The x coordinate corresponds to the position of the point O with respect to the spike tip. The straight line approximating the experimentally registered positions of the point O at different times was used to calculate the mean velocity of its motion along the spike surface. According to experimental data, the velocity of the point O from the frontal face of the cylinder to the spike tip is $V_O = 335$ m/sec. Apparently, the gas-flow velocity on the right of the point O is transonic and will be supersonic in the next phase of the cycle of self-sustained pulsations (see below).

The free stream impinging on the spike tip collides with the reverse supersonic flow from the zone Z', which leads to emergence of radial motion of the gas and a new wave W_1 (see Fig. 3; $\tau = 0.59$ and 0.61) present in the next cycle of self-sustained pulsations.

After that, the gas moving in the radial direction turns again and flows downstream, covering the head part of the separation zone Z' (Fig. 6). The gas moving along the spike surface from the frontal face of the cylinder toward the spike tip turns and becomes compressed. A local supersonic flow region bounded by the shock wave W_s is formed near the spike surface.

Figure 7 shows the emergence ($\tau = 0.71$) and evolution of the wave W_s (marked by an arrow) at different times. Its radial size is seen to increase in time, and its intensity decreases at the final stage; as a result, the shock wave degenerates into a compression wave (because the difference in pressure between the spike tip and the frontal face of the cylinder decreases).

The assumption that the reverse flow velocity near the spike surface is supersonic is confirmed by Fig. 8, which shows the wave W_s (marked by an arrow) for different values of the spike length L. For $L = 70$ mm ($L/D = 1.4$), the velocity of the point O was determined as $V_O = 500$ m/sec. For the experimental parameters used, the gas velocity behind the point O is supersonic; therefore, the wave W_s is a shock wave. As the spike length is reduced, the velocity of the point O decreases [in the case $L/D = 1$, it equals 335 m/sec (see Fig. 5)]. For a dimensionless spike length $L/D = 0.85$, the wave W_s can still be seen in the photographs (see Fig. 8); for $L/D = 0.8$, the wave disappears. As the flow structure in the corresponding phase of the cycle of self-sustained pulsations remains essentially unchanged for different spike lengths, we can assume that there is a local supersonic reverse flow region near the side surface of the spike in this phase of the cycle of self-sustained pulsations in the entire range of the values $0.85 \leqslant L/D \leqslant 1.45$ where the wave W_s is observed. For $L/D = 1$, the time of existence of this region is $0.76 \leqslant \tau \leqslant 0.91$, i.e., 50 μsec.

The increase in reverse flow velocity near the spike surface with increasing spike length can be explained as follows. For a longer spike, the angle of inclination of the wave W_c to the axis at the moment when the wave W_1

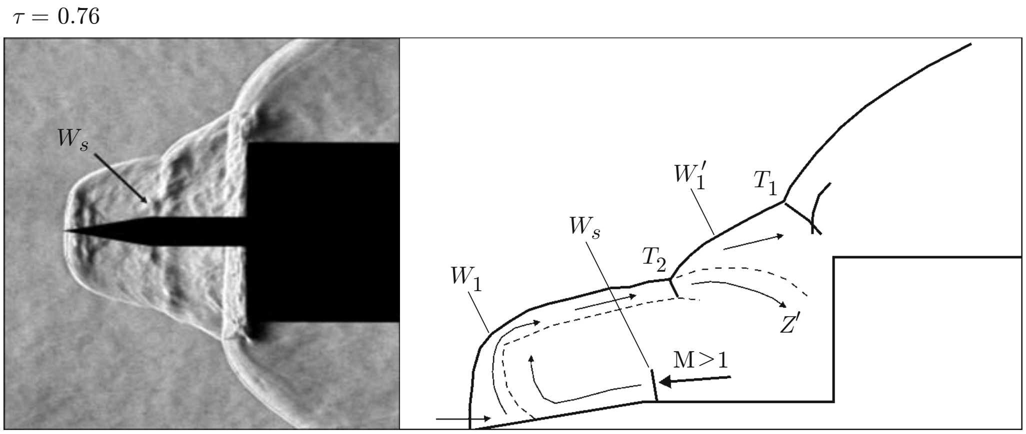

Fig. 6. Schlieren picture and simplified pattern of the flow with a supersonic flow region located near the side surface of the spike between the shock wave W_s and the frontal face of the cylinder.

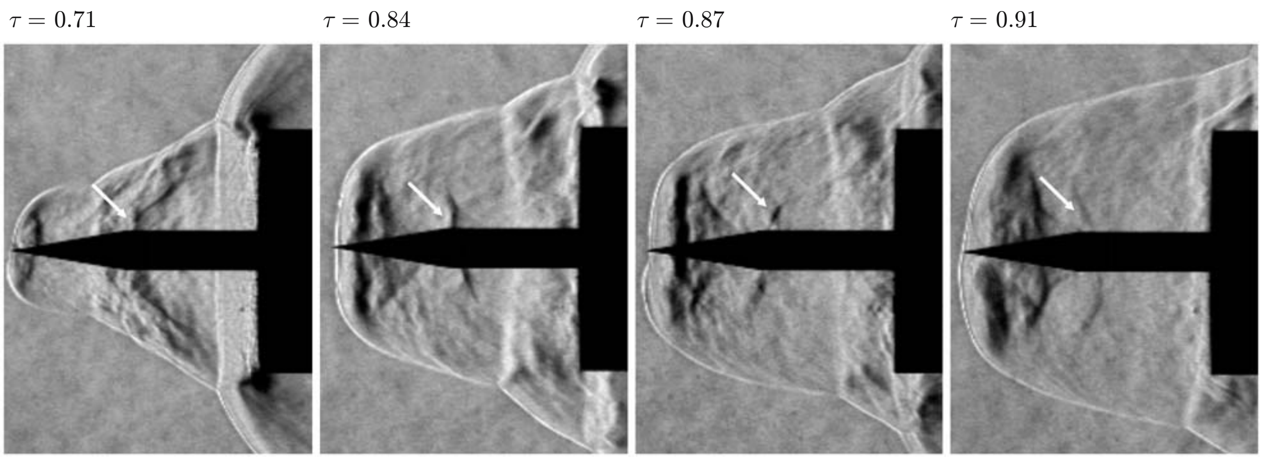

Fig. 7. Emergence and evolution of the shock wave W_s.

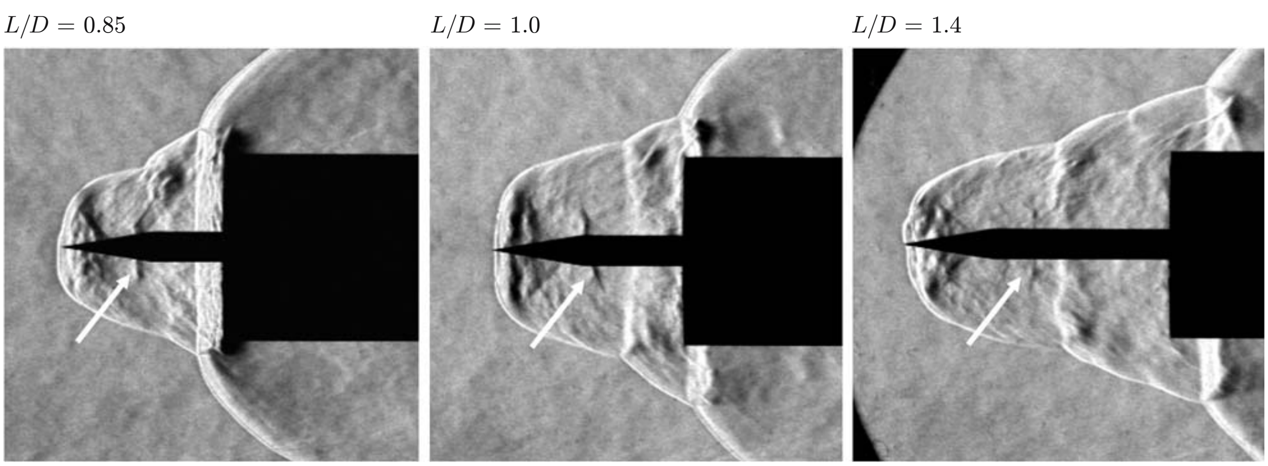

Fig. 8. Schlieren pictures with the shock wave W_s for different spike lengths.

approaches the frontal face of the cylinder is smaller than that for a shorter spike. The total pressure loss behind such a wave is smaller; hence, a greater pressure is generated near the frontal face of the cylinder by the jet J being decelerated on the frontal face of the cylinder. Simultaneously, the pressure behind the wave W_c near the spike tip is smaller, because the angle of inclination of the conical wave W_c to the axis decreases with increasing L/D. Thus, the pressure difference between the frontal face of the cylinder and the spike tip increases with increasing L/D; hence, the reverse flow velocity also increases.

Conclusions. The experiment performed allowed refining the structure of the reverse flow in the forward separation region for a free-stream Mach number $M_\infty = 6$. This zone is shown to appear near the spike tip from the moment when the bow shock wave W_1 starts moving toward the frontal face of the cylinder. The existence of a local supersonic zone in the forward separation region in one of the phases of the self-oscillatory process is validated. For $L/D = 1$, the local supersonic flow region exists in the time interval $0.76 \leqslant \tau \leqslant 0.91$. For the model with a sharp spike ($\varphi = 10°$), a region of a supersonic reverse flow is registered near the side surface of the spike for $0.85 \leqslant L/D \leqslant 1.45$.

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