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PROBLEM OF FIRING PLANAR NOZZLES IN SHOCK TUBES

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UDC 533.6

Numerous recent investigations are concerned with studying the propagation of shock waves in channels with variable cross sections. There is no rigorous description of all details of such flow, so that each investigation is carried out based on a chosen simplified model. In particular, in order to analyze processes related to firing nozzles in shock tubes, flow models taking into account the passage of the primary shock wave along the nozzle, the contact surface, the secondary shock wave, and nonstationary rarefaction waves are widely used [1]. Such models permit determining the trajectory of the shock waves, which in many cases [1-4] coincide with the experimentally observed trajectories, although the viscosity of the gas and the two-dimensional nature of the flow were not taken into account in the calculations. The effects indicated are manifested most strongly in the supersonic part of the nozzle, near its walls, when the secondary shock wave interacts with the boundary layer, causing separation of the flow [1, 5, 6]. At the present time, there is no clear idea of how the flow separation affects the flow parameters and the continuance of firing, measured through the lateral walls of the planar nozzle. The possibilities of computational methods are limited due to the absence of criteria for separation in a nonstationary flow and spread of separation data in stationary flows [1]. Also, the relation between the flow separation from diverging and from parallel walls of the nozzle is not clear. We note that when the flow is visualized optically [1, 5], the flow separation from the diverging walls is clearly manifested, but the effects are not observed on the parallel walls due to the small optical thickness of the imhomogeneities. At the same time, the schemes for measuring the optical amplification are more sensitive to the effects on the parallel

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walls of the nozzle, since the flow is probed through these walls by laser radiation [7]. Clearly, in this case, simultaneous measurement of the coefficient of amplification at several points along the axis, in principle, permits determining the continuance of firing in different sections of the nozzle and reconstructing the shock wave trajectories along the nozzle and the point of flow separation from the lateral and parallel nozzle walls. However, the complicated nature of the flow behind the front of the primary shock wave complicates the detailed interpretation of the signals obtained, and it is usually possible to distinguish only the basic characteristics, corresponding to the beginning and end of the firing process. According to [7], the constant level of amplification (absorption) of the probing radiation is established only after the flow separation zones passes along the nozzle, so that from the measurements it is possible to reconstruct its trajectory along the nozzle. Such an investigation is carried out in this work, and, in addition, the experimental results are compared with the wave picture of the firing process, obtained from a calculation. The results of such a comparison permit judging the magnitude of the error in the computation of the continuance of firing when effects related to full separation are not taken into account in the calculations.

1. In the experiments, we used a planar wedge-shaped nozzle with rectilinear generatrices, aperture angle $\alpha = 30°$, and critical section height $h^* = 2$ mm. The nozzle had a length $l = 120$ mm and the radius of curvature of the subsonic part was $r = 4$ mm.

The flow was probed by CO_2 laser radiation simultaneously in three sections, situated at distances of 28, 49, and 70 mm from the critical section of the nozzle. Film sensors, namely platinum resistance thermometers deposited by vacuum sputtering on a glass substrate, were placed on these sections in the side wall of the nozzle parallel to the flow. The resistance of each sensor was about 40 Ω. They were included in a bridge circuit and the signal was fed through an amplifier with a transmission band of 1 mHz into an oscillograph. In order to simplify the procedure of interpreting signals, related to the deflection of the probing beam and heating of the film sensor with the passage of shock waves and the separation zone, the results of an optical investigation carried out in [7] were used. The work was carried out on a shock tube with the inner diameter of the low-pressure chamber equal to $D = 496$ mm. Nitrogen with a small (up to 15%) admixture of carbon dioxide gas, necessary for recording the absorption of IR radiation, was used as the working gas. The experimental arrangement and the measurement procedure are described in [8], while here we shall only point out that the starting pressure of the mixture varied from $1.3 \cdot 10^{-5}$ to $5.2 \cdot 10^{-5}$ MPa, while the velocity of the shock wave v_S varied from 1 to 1.4 mm/μsec. Measurements of the stagnation parameters behind the reflected waves [9] showed that in the range studied, the pressure drop at the inlet to the nozzle varied from 4 to 10 MPa, while the stagnation temperature varied from 1300 to 2000°K. We did not use a diaphragm in front of the channel inlet, so that the initial conditions in the nozzle and in the low-pressure chamber coincided prior to the experiment.

2. In the computational study of the firing process, we examined the flow of a nonviscous and non-heat-conducting gas in the expanding part of the nozzle, which was described by nonstationary equations of gasdynamics in the channel approximation. In integral forms, these equations have the form [2]

$$\oint_{\gamma} (x)\,[\mathbf{a}dx - \mathbf{b}dt] = \int_{\Omega}\int \mathbf{f}Q'(x)\,dxdt, \qquad (2.1)$$

where

$$\mathbf{a} = \begin{Bmatrix} \rho \\ \rho u \\ \rho\left(\varepsilon + \frac{u^2}{2}\right) \end{Bmatrix}; \quad \mathbf{b} = \begin{Bmatrix} \rho u \\ p + \rho u^2 \\ \rho\left(\varepsilon + \frac{u^2}{2}\right) + pu \end{Bmatrix}; \quad \mathbf{f} = \begin{Bmatrix} 0 \\ p \\ 0 \end{Bmatrix};$$

ρ is the density; u is the flow velocity; p is the pressure; ε is the enthalpy; x is the distance from the critical section (the x axis is directed along the nozzle axis); t is the time; $Q(x)$ is the area of the transverse section of the nozzle; and, in addition, if $y = y(x)$, then the equation of the generatrix of the channel wall in the xy plane, in the planar case, is $Q(x) = y(x)$.

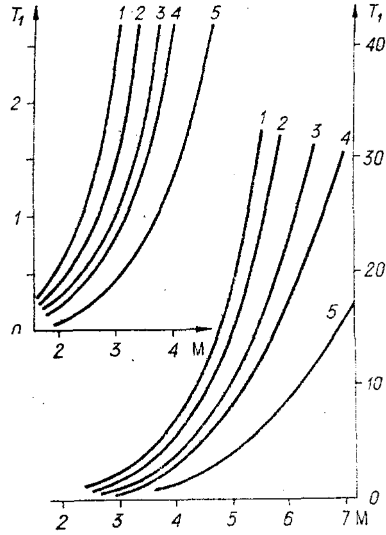

Fig. 1

Equation (2.1) is integrated along an arbitrary closed contour Γ, bounding the region Ω in the xt plane. Taking into account the boundary conditions in the critical section of the nozzle, the conditions on the primary jump, and the conditions of piecewise joining of continuous solutions on the secondary shock wave, system (2.1) was integrated numerically using Godunov's methods [10]. Effects related to the two-dimensional nature of the flow near the throat of the nozzle were taken into account by introducing a special flow rate factor [2]. A moving grid, fixed to the discontinuities and having increased density in regions with high gradients, was used. Surfaces with strong discontinuities in the parameters were distinguished by ongoing monitoring of the solution using the basic operation of Godunov's method, namely, calculating the disintegration of an arbitrary discontinuity. The number of computational points was automatically increased as the dimensions of the perturbed region increased.

The Mach number M* of the primary shock wave in the critical section of the nozzle and the initial distribution of parameters were determined from a solution of the problem of the disintegration of an arbitrary discontinuity at the time of reflection of the shock wave from the end face of the low-pressure chamber t = 0. Here, the parameters to the left of the discontinuity corresponded to stationary boundary conditions and were determined assuming that the gas is accelerated in a stationary manner out of the region behind the reflected shock wave, while the velocity of sound is reached in the critical section of the nozzle. The parameters to the right of the discontinuity were assumed to equal the parameters of the unperturbed gas, and the change in the area of the channel at the time of the disintegration of the discontinuity was not taken into account. The values of M* obtained in this manner practically coincided with the results of calculations of the quantity M* carried out in [11]. Calculations using the procedure described permitted determining the trajectories of primary and secondary shock waves when firing the nozzle under different conditions. The results obtained are presented in Figs. 1 and 2 in dimensionless coordinates $T_i = f(M)$.

Here we used the following notation: $T_i = t\frac{2\tan\frac{\alpha}{2}}{h^*}a_i$, a_i is the velocity of sound in the i-th region of the flow, i = 2, 1, respectively, for parameters at the nozzle inlet and in the unperturbed gas filling the nozzle prior to the experiment; and M is the stationary value of Mach's number. According to [11], the shock-wave trajectories, presented in these coordinates, independent of the geometry of the wedge-shaped nozzle for which they were obtained, are functions only of the number M* as a parameter. We note that recalculating the results presented in Figs. 1 and 2 in order to construct trajectories in space–time coordinates requires $\alpha > 30°$ corrections, taking into account wavefront curvature, as is done in [1]. Curves 1-6 in Figs. 1 and 2 correspond to M* = 1.775, 2.39, 3.52, 4.57, 9.15, and 12.6. The dashed curves (Fig. 2) permit calculating the filling time of the nozzle by the stationary gas flow, i.e., it determines the magnitude of the minimum firing time [11]; the arrows indicate sections I, II, and III, in which the measurements were carried out. The

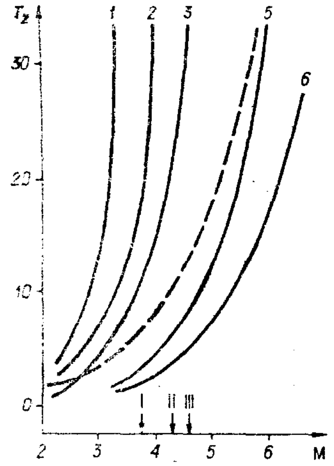

Fig. 2

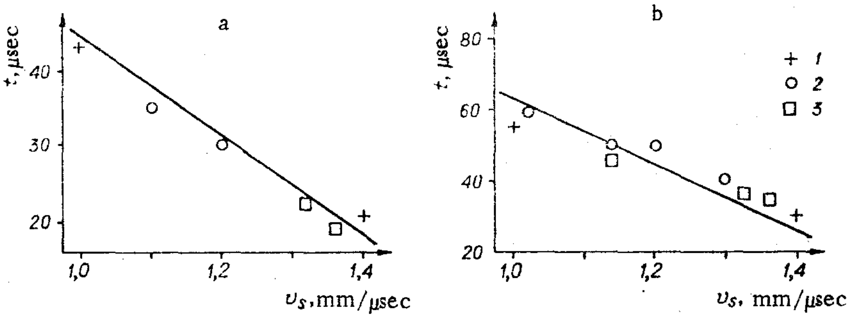

Fig. 3

results of the calculations show that the primary shock wave (Fig. 1) quite rapidly leaves the nozzle in all regimes, while the secondary wave, in regime 1, can occupy a stationary position within the nozzle, hindering the establishment of a supersonic flow in sections I-III and in sections II and III for regime 2, and only in regimes 3-6 is the nozzle completely emptied. Comparing the trajectories of the secondary shock waves with the curve of the minimum firing time (Fig. 2), we should note that for $M^* = 1.775$, 2.39, and 3.52, the firing process is determined by the secondary shock wave, while for $M^* = 9.15$ and 12.6, it is determined by the rarefaction wave.

3. The computed results are compared with experiments in Figs. 3 and 4. All times in the graphs were measured from the time that the shock wave arrives at the first measuring section in the nozzle ($x = 28$ mm, $M = 3.75$).

The following notation was used for the analysis of the results: (1) signals in the film sensors; (2) signals from the photodetector; (3) photographic scans [7]. The computed times (continuous line) were obtained by recalculating the data in Figs. 1 and 2 for conditions under which the measurements were carried out. The satisfactory agreement between the experimental and computed times of arrival of the primary shock wave in the second (Fig. 3a) and third (Fig. 3b) measuring sections of the nozzle should be noted. The spread in the experimental points is related to the error in analyzing the results and does not exceed 10%. Figure 4a-c presents the computed times of arrival of the secondary shock wave in sections I, II, and III of the nozzle, respectively. The points on the graph correspond to the measured arrival times of the separation zone in these sections. From a comparison of experiment and calculation, it is evident that the separation zone with low velocities v_s lags considerably behind the secondary shock wave and, in addition, the distance between them increases as the distance between the measuring section and the throat of the nozzle increases. This indicates the development of splitting of the secondary jump as it moves downstream, which agrees completely with the optical data [1, 5, 6].

We must make two important remarks concerning the results presented in Fig. 4. Under the conditions examined, the effect of the separation on the velocity of the secondary jump will be a maximum for values of $v_s = 1$ mm/μsec. However, even in this case, according to

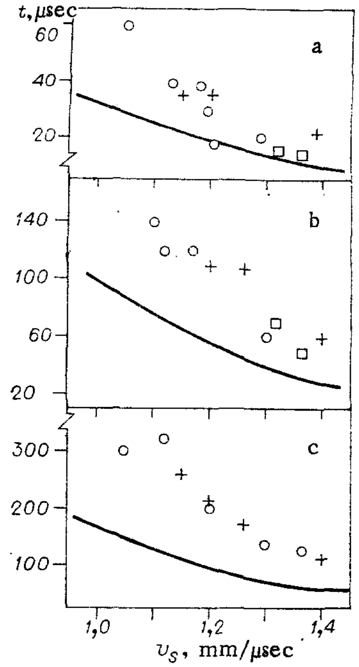

Fig. 4

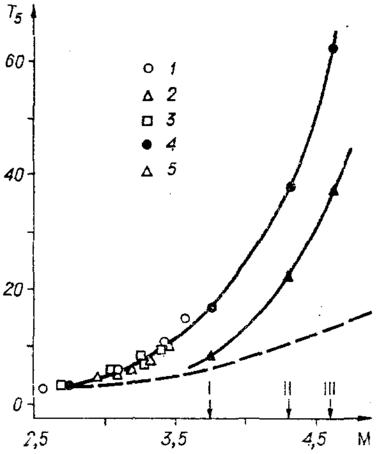

Fig. 5

[2], the one-dimensional formulation of the calculation used in this work permits achieving agreement with experiments [3, 5]. This justifies the use of the computational procedure for determining the shock-wave trajectories under the conditions of the present investigation.

The other remark is related to the fact that the separation zone lags behind the front of the secondary shock wave. The results in Fig. 4 show that the firing time in the entire range of experimental conditions is determined by the motion of the separation zone along the nozzle and not by the secondary shock waves. It is evident that the separation of the flow leads to the fact that the firing time increases by a factor of 2 compared to the magnitude determined by the motion of the secondary shock wave along the nozzle. The results of the measurements are compared with the experimental data in [5] in Fig. 5, from which it is evident that the trajectories of the zone where the flow separates from the diverging walls along the nozzle, obtained for nozzles of various sizes (see Table 1), fall onto a single curve. The agreement between the results of this work and the work in [5] indicates that under the conditions investigated the separation of the flow from diverging and from parallel walls of a planar nozzle obeys a single law, while the trajectories of the separation points along the nozzle coincide. Comparing the measured value of the continuance of firing with the magnitude of the minimum time, we note that for v_s = 1 mm/μsec,

TABLE 1

Number of point in Fig. 5	α, deg	h^*, mm	M^*	v_s, mm/μsec	Reference
1	30	6	3,52	1,03	[5]
2	20	6	3,52	1,03	[5]
3	30	9,7	3,52	1,03	[5]
4	30	2	3,6	1,05	This work
5	30	2	4,7	1,4	

the triggering time in the first section is twice as great as the minimum value, while in the third section it is more than four times greater. As the velocity v_s increases, the firing time decreases, remaining appreciable; however; and in the third section of the nozzle it is almost three times greater than the minimum value. In conclusion, we point out the fact that the increase in the continuance of firing, measured along the nozzle axis, is related to the separation of the flow from the parallel walls, first noted in this work, although similar phenomena accompanying separation from diverging walls of a planar nozzle were already discussed in [1, 5].

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