STRUCTURE OF PULSED GAS JETS FLOWING OUT OF SUPERSONIC NOZZLES

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UDC 533.601.1:534.220.2

The nonstationary gas flowing out of sonic nozzles was considered in [1-4]. The study of a nonstationary jet flowing out of supersonic nozzles is a development and continuation of these experimental investigations.

A large number of parameters characterizing the outflowing gas and the residual gas of the pressure chamber, as well as the geometry of the outflow conditions are determined in the general formulation of the problem of motion of a front of outflowing material and its accompanying perturbations during the formation of a pulsed jet. If the stagnation parameters of the outflowing gas are limited to values at which it can be considered as ideal and perfect, and the experiment is organized so that the residual and working gases are identical, then the number of governing parameters is reduced. Within the framework of the constraints accepted, the outflow can be described by the following generalized parameters:

$$r/r_*,\ \theta,\ \tau c_*/r_*,\ p_*/p_\infty\ ,\ T_*/T_\infty,\ \gamma,\ \overline{G},$$

where r is the radius-vector coordinate, θ is the polar angle, r_* is the radius of the critical nozzle section, c_*, p_*, T_* are the sound speed, pressure and temperature in the critical nozzle section, p_∞, T_∞ are the pressure and temperature in surrounding space, $\overline{G}$ is a factor describing the nozzle geometry, γ is the ratio of the gas specific heats, and τ is the time of the stage of the process.

The conical nozzles used in this research were computed by using the geometric Mach number at the exit for the stationary flow mode 4.8; 4.5; 3.2 ($\gamma = 1.4$) with an identical critical section diameter. The nozzle was mounted in the endface of a shock tube and the gas heated by the reflected shocks escaped into a chamber with reduced pressure ($p_\infty = 5$-40 mm Hg).

Variation of the incident wave Mach number in the tube provided the opportunity to vary the stagnation parameters of the outflowing gas and to model the nonstationary jet by means of the parameters p_*/p_∞, T_*/T_{00}. The initial off-design value p_*/p_∞ varied also because of the change in pressure in the pressure chamber p_{00}. Modeling the jet in the parameters $\overline{G}$ and γ was realized by mounting nozzles of different configurations in the tube endface and by using different gases.

The incident wave velocity in the tube was measured during the experimental investigations performed, and successive stages of the outflowing material motion and its accompanying perturbations were recorded by a Schlieren method in the pressure chamber for known initial parameters. The time of recording the outflow stage relative to the beginning of the outflow is fixed clearly on the Schlieren photograph.

Illustrations of the successive change in the structure of a nonstationary carbon dioxide gas jet are shown in Fig. 1 for different nozzles. The nozzle characteristics are given in Table 1.

The results obtained during the outflow of gases heated by shocks with $M_0 = 2.5$-3.5 reflected from the tube endface are considered in this paper.

The gas parameters behind the wave reflected from the shock tube endface with the mentioned Mach values of the incident wave are assumed to be the equilibrium values. The critical sound speed in the generalized coordinates was assumed to be frozen. Qualitatively, the maximum deviation of this value from the corresponding equilibrium value in the parameter range investigated is not more than 5%.

The picture of the wave structure of a nonstationary sonic jet is described in [2]. The structure of the flow being developed during outflow from a supersonic nozzle is distinctive in that it has a prehistory of flow formation in the nozzle. In this case, the front of the outflowing material approaches the nozzle exit, before which the shock being formed moves. The secondary compression shock, which is seen well in a gas escaping

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Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 56-65, January-February, 1979. Original article submitted April 27, 1978.

TABLE 1

Nozzle number	M_a	d_*,mm	d_a,mm	φ_a
1	4,8	4,32	20	15
2	4,5	4,36	18	10
3	3,5	4,32	10	15

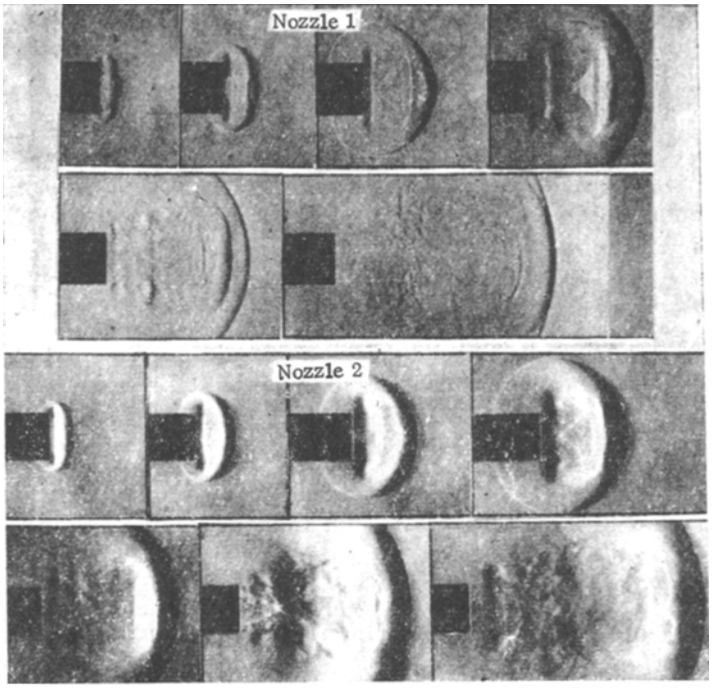

Fig. 1

from a slot is scanned through the vortex rings escaping from a circular hole (sonic nozzle) and a supersonic nozzle. In many cases several secondary, successive waves occur. In addition to the secondary wave or the system of secondary shocks in the initial stage of exhaust from a nozzle, a system is observed which is similar in wave structure to a stationary underexpanded jet which varies with time, a bridge-shaped shock (Mach disk) of this structure diminishes during downstream movement and degenerates into an X-shaped structure which vanishes altogether. This is characteristic for nozzles 1 and 2, i.e., for nozzles with a large "geometric" Mach number at the exit. In those cases when the secondary shock is seen on the Toepler diagrams during the flow development and its displacement along the axis, the change in its shape can be traced. At large times from the beginning of the outflow it is already not an element of a sphere, and at $t \geq 100$ μsec the wave becomes planar. For $t \geq 150$ μsec it vanishes in Ar, and N_2, while for $t \geq 300$ μsec it vanishes in CO_2. Vortex rings form at the nozzle edge in the outflowing gas, and their number is less, as a rule, than in the case of outflow from a sonic nozzle. The rings increase in size during the flow development and dissociate, and the jet is turbulized. After 100-150 μsec from the beginning of the outflow, under the geometry conditions of the experiment when the vortex rings merge and form a developed turbulent structure, a system of perturbations originates in the region between the surface and the shock going along the pressure chamber gas. The perturbation closest to the front of the outflowing material duplicates its shape, and the whole system of perturbations moves downstream.

No wave structure formation characteristic for a stationary jet corresponding to the initial off-design was observed in the time (up to 400 μsec) and governing parameter range investigated.

The quantitative information obtained from the photographs examined consists in determining the regularities of the displacement of the outflowing material front and the wave front ahead of it in space. These regularities, represented in generalized parameters, describe the change in time of the structure of any jets in the starting modes.

TABLE 2

Nozzle number	Gas / Coeff.	CO_2	N_2	Ar
1	A	4,26	3,16	2,01
	α	0,64	0,675	0,76
2	A	3,86	3,00	2,59
	α	0,86	0,70	0,72
3	A	2,01	2,12	1,57
	α	0,82	0,78	0,80

TABLE 3

Number Nozzle	Gas / Coeff.	CO_2	N_2	Ar
2	B	2,04	1,41	0,95
	β	0,74	0,84	0,86
3	B	1,16	0,84	0,55
	β	0,90	0,95	0,96

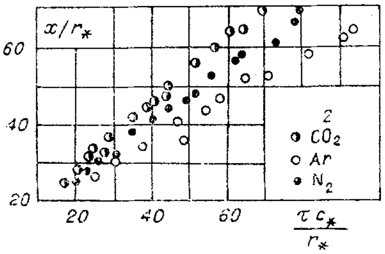

Fig. 2

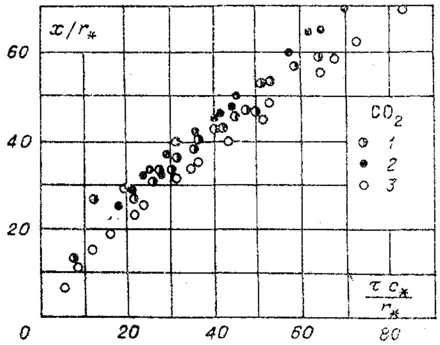

Fig. 3

Let us examine the motion along the jet axis ($\theta = 0$) of a front of material K and the wave ahead of it S in the coordinates $\bar{x}=x/r_*$, $\bar{t}=\tau c_*/r_*$. In these coordinates the experimental points lie on one curve for each of the gases under investigation and for each nozzle. Experimental points characterizing the motion of the wave S during the outflow of CO_2, Ar, and N_2 from nozzle 2 are presented in Fig. 2. The appropriate dependences for nozzles 1 and 3 are analogous. Comparison of the primary wave motions for the nonstationary outflow of CO_2 from different nozzles is presented in Fig. 3.

The results of generalizing the experimental data in the coordinates x and t are presented in the tables. Values of the exponents and the coefficients in front of the power term in a formula of the form $\bar{x}=A\bar{t}^{\alpha}$ which describes wave motion ahead of a front of material are presented in Table 2. A definite regularity in the numerical values obtained is observed during the passage from CO_2 to Ar (with the growth in the number γ), however the data on N_2 drop out of the regularity for nozzle 3, and this circumstance requires further investigation.

Taking account of the difference in nozzle geometry, it is expedient to start with the change in the origin of the motion of the gradient stream domain along the axis by eliminating the nozzle length and shifting the time origin correspondingly. Intersection of the origin will be sufficiently correct if it is performed by using the approximation obtained above. Extrapolation of the graphical dependences of $\bar{x}$ and $\bar{t}$ to the coordinate of the nozzle exit $x=l$ yields the value of the time t_{i0} corresponding to the wave emergence from the nozzle exit.

Passage to the new coordinates

$$\bar{x}' = (x - l)/r_*, \quad \bar{t}' = \tau c_*/r_* - t_{i0}$$

and construction of the approximate relationships in these coordinates result in a satisfactory extension of the data over all the nozzles for each of the gases.

The following equations of wave motion ahead of the front of material are obtained:

$$\bar{x}' = 1.44\bar{t}'^{0.86} \text{ for } CO_2,$$

$$\bar{x}' = 1.38\bar{t}'^{0.88} \text{ for } N_2.$$

$$\bar{x}' = 0.63\bar{t}' \text{ for Ar.}$$

No analogous generalization is obtained in the coordinates used for the material front motion, which is apparently assocaited with the more substantial influence of the flow stage in the nozzle on the regularity of free stream motion.

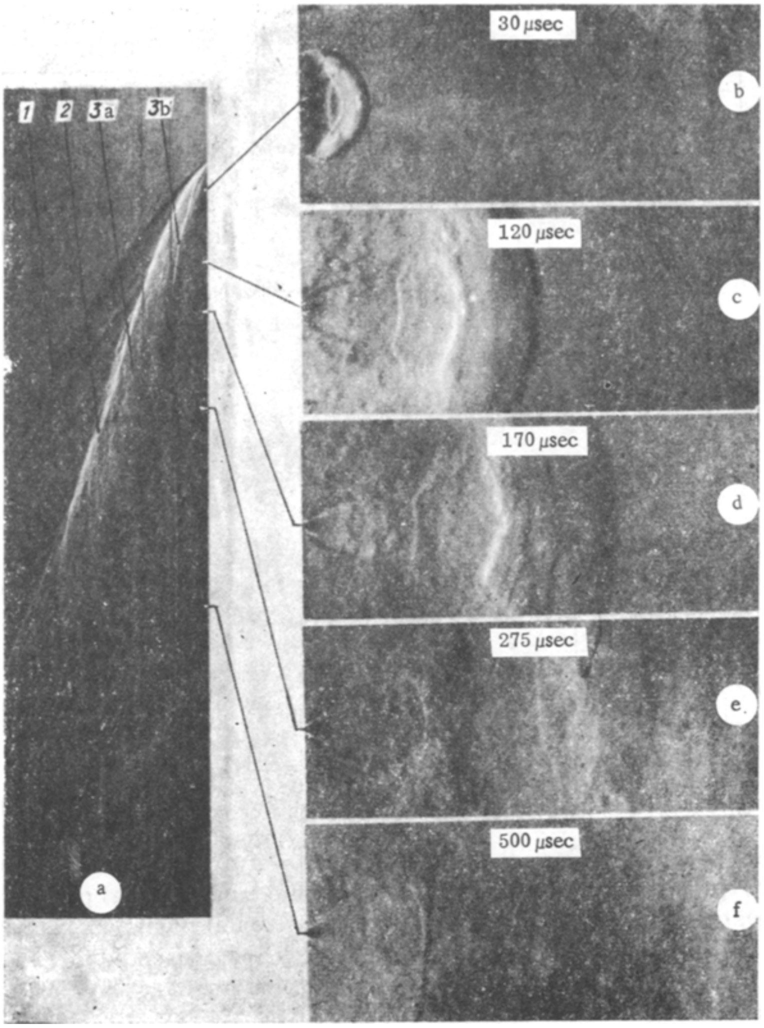

Fig. 4

The data on the material front motion are generalized satisfactorily by the dependence of the form $\bar{x}=B\bar{t}^{\beta}$ for each gas and nozzle separately in the whole range of initial values considered. The coefficients B and β are represented in Table 3 for nozzles 2 and 3.

The nonstationary wave structure of pulsed jets is characterized in a sufficiently broad range of initial parameters by the presence of analogs of the Riemann wave and the Mach disk in stationary jets, secondary compression waves.

Many papers [5-12] are devoted to the determination of the location and size of the Mach disk and the Riemann wave in a stationary jet. However, the assumptions taken for the foundation of the computation hypotheses are contradictory [5-8] and the empirical relationships are not sufficiently general. An analysis of the secondary wave behavior in the jet formation stage can and should yield the information needed for a physically well-founded selection of the initial hypotheses for the computation of the location and size of the Mach disk and Riemann wave in stationary jets as well.

The question of the secondary compression wave motion during jet formation is examined in detail below.

Recording of the successive outflow stages in this series of experiments was performed both by the method of frame-by frame photography by using a spark light source (flash time 1 usec, frame size 45 × 100 mm^2), and by the method of continuous scanning by using an IFK-120 pulsed lamp and a photorecorder of the type ZhFR-1. These two recording methods supplemented each other by assuring high time and space resolution. A careful analysis of the jet structure was accomplished by means of the photographs obtained in the frame-by-frame survey, and the development of the flow picture in time was analyzed by means of the continuous sweep in addition.

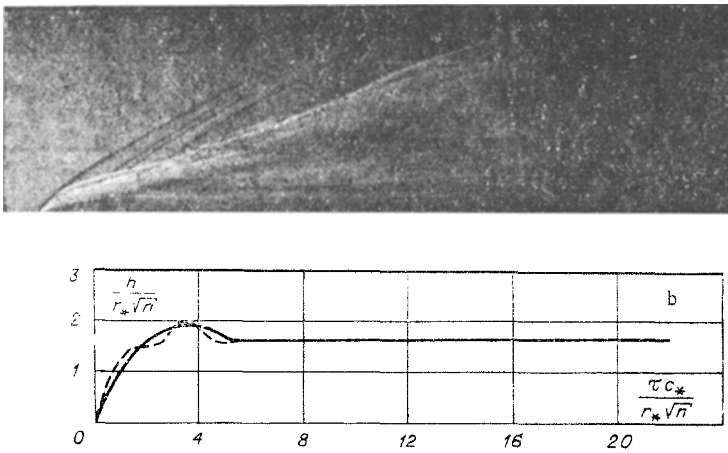

Fig. 5

Sweeps of the nitrogen outflow from plane (Fig. 4a) and axisymmetric (Fig. 5a) nozzles are represented in the photographs. Let us note the characteristic lines on the Toepler photographs presented: 1) trajectory of primary shock surface motion; 2) contact surface of the outflowing gas; 3a and 3b) secondary shocks in the outflowing gas. The five succeeding stages in nitrogen outflow from a plane nozzle, obtained by using the spark light source, are represented in Figs. 4b-f.

Let us examine the flow singularities which can be clarified in a comparison between the frame-by-frame and the continous photorecording processes. For both the planar and axisymmetric outflow the gas motion occurs with intense vortex formation. The very complicated interaction between the vortices within the outflowing gas is reflected in both the motion trajectory of its front of coarse and fine-scale pulsations, which results in turn in the generation of sonic and stronger density perturbations. Traces of these perturbations are seen between the motion trajectories of the primary shock and the contact surface in the photographs, and which as any perturbation behind a shock, reach it, make up, and are one of the causes spoiling the self-similarity of the flow.

We shall not examine the secondary wave 3a which occurs near the outflowing gas front in this paper but we shall study wave 3b which tends to occupy the quasistationary location of the Riemann wave and the Mach disk. On the basis of an analysis of a large quantity of sweeps, the nature of the compression wave motion in the outflowing gas, the nonstationary Mach disk (3b) is detected. A graph of the motion of the nonstationary Mach disk as nitrogen flows out of a sonic nozzle of 4-mm diameter ($n=p_a/p_\infty$ is the off-design, p_a is the pressure at the nozzle exit, h is the spacing along the axis from the nozzle exit to the nonstationary Mach disk) is represented in Fig. 5b in the dimensionless similarity coordinates $h/r_*\sqrt{n}$ and $\tau c_*/r_*\sqrt{n}$. It is seen from Fig. 5b that the nonstationary Mach disk crosses its stationary location by 10-15% in the modes considered during jet formation and then returns back to occupy the quasistationary location after ~140 μsec from the beginning of the outflow. In different tests, the amplitude of the vibrations and the frequency have a large spread. The mean values of the vibrations amplitude of the Mach disk coordinates are ~7% and of the vibrations frequency ~15 kHz. The quasistationary Mach disk location realized in our experiments is in satisfactory agreement with that proposed in [9] for stationary jets.

The formation of a Riemann wave in three-dimensional jets has been investigated for N_2, Ar and CO_2 outflows from planar sonic nozzles with the critical section dimensions: 1) 1.5×40 mm^2, 2) 2.2×40 mm^2, 3) 0.8×32 mm^2. One of the most important characteristics of the wave structure is the distance to the Riemann wave in plane stationary jets, which is proportional to n. This same criterion was used to analyze the motion of a nonstationary Riemann wave in the formation of a three-dimensional jet. A dependence of the Riemann wave motion in time in the initial stage (to 140 μsec) is constructed in the dimensionless coordinates $h/r_*n=f(\tau c_*/r_*n)$. The dependences obtained for different gases were approximated by power functions of the form $y=Ax^\alpha$ by using the MHK, where A and α are presented in the table in Fig. 6.

Let us examine the question of the applicability of the model of flow formation from a source to the flows under investigation. Flows from cylindrical and spherical sources in the aspects of interest to us turn out to be qualitatively analogous, consequently, unless stipulated otherwise, we shall not distinguish between them. The primary shock which forms in the gas of the surrounding space slows down with time and degenerates into a sound wave at infinity. The contact surface also moves with retardation and as the time tends to infinity, its

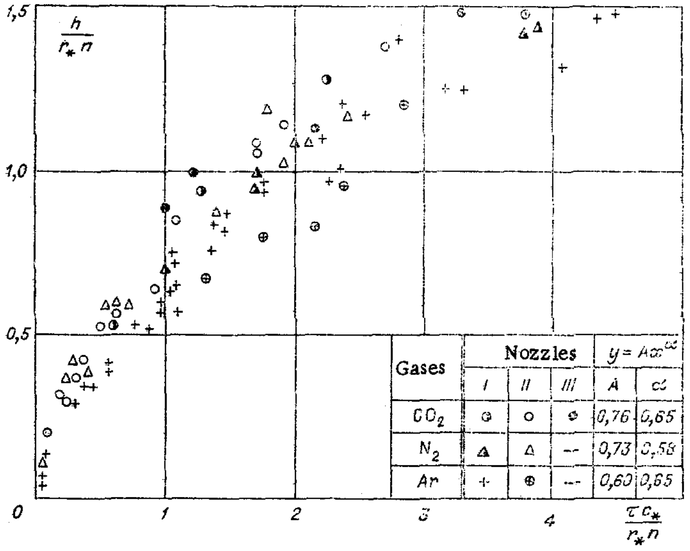

Fig. 6

velocity diminishes to zero, but the pressure approaches the pressure in the surrounding space asymptotically. Retardation of the contact surface motion is caused by the fact that the mass of gas enclosed between the wave and contact surface grows with the course of time, while the area of the contact surface also increases in time but the influx of momentum in the expanding gas system remains constant. Retardation of the contact surface in the initial stage of the expansion results in compression of the impinging gas. The compression first occurs isentropically, and with the growth of time in the secondary shock whose intensity increases as the outflow develops. This shock tends to occupy a stationary location and modes [13] are possible when it passes its stationary location and only then returns to it. The secondary wave moves over the nonstationary rarefaction wave in the initial expansion stage, and intersects it in the course of time (see, e.g., the experiments in [14]), and further motion occurs on a stationary rarefaction wave. Under certain conditions, the secondary shock starts to move along the stationary rarefaction wave almost at once (hypersonic source, pressure not very low in the surrounding space). In its general features, such is the qualitative picture of the flow according to [13, 15].

The asymptotic laws for the behavior of the characteristic flow surfaces are found in [13] within the framework of the theory of an ideal fluid. The approximate laws for the motion of the same surfaces in the initial expansion stage are found in [15] in the hypersonic source approximation, the accuracy of the formulas proposed is $\sim 10\%$ (it is assumed that the domain thicknesses are $r_1 - r_2$ and $r_2 - r_3 \ll r_1$). Using certain analogies with selfsimilar problems on the motions of convergent shocks and flows caused by an expanding piston, the author of [15] compiled the mass and energy balance equations from which the appropriate relationships were obtained for the characteristic surfaces. Moreover, the solution of the nonstationary problem of flow from a stationary cylindrical and spherical source is performed numerically in [15], taking into account the viscosity and heat conductivity in the whole stage of flow formation. The results of the numerical computations verified the qualitative picture of the process which was described above, and disclosed slight influence of the Reynolds number on the flow.

Let us examine the question of how the problem solved in [13, 15] and the problem of jet formation are related. It is known that the solution for the steady flow from a stationary source is applicable to the central part of a stationary jet. It would be careless to carry such a method over to a nonstationary jet since:

1) It is impossible to set the stationary isentropic rarefaction wave existing in the flow from a source throughout the time of process development into a one-to-one correspondence with some flow domain in the nonstationary jet.

2) After a certain time the secondary shock in the model of nonstationary flow from a source occupies the stationary position. However, in the experiments we performed with N = 20-200, the jet formation is accompanied by two secondary shocks. The first of them, arranged closer to the contact surface (3a), is present in experiments with different values of the governing parameters ($n \gtrsim 1$). Its existence is apparently associated with the presence of a quite extensive zone of reciprocal vortex motion near the outflowing gas front, and in contrast to the wave 3b, the secondary wave 3a in the gas return motion zone is called the "dynamic secondary

wave." The secondary shock (3b, Figs. 4 and 5) is the analogy of the stationary Riemann wave and Mach disk in the experiments under consideration and for $n < 1$ should not be formed as is verified by experiments performed with plane and axisymmetric nozzles (geometric Mach number at the exit 3.5, and $\gamma = 1.4$).

3) The characteristic surface locations computed numerically in [15] for a gas flowing out of a source agree only qualitatively with the locations of the corresponding surfaces measured experimentally in nonstationary jets. The discrepancy is 30% and more.

The results presented, while not exhaustive, afford the possibility, however, of reproduction of the formation of the wave structure of pulsed jets in the nonstationary flow stage for Mach number ranges on the nozzle exit which are of practical interest and for values of γ of the outflowing gases.

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