$$v_{1r}\frac{\partial p_0}{\partial \xi} + \frac{v_{0\omega}}{\xi}\frac{\partial p_1}{\partial \omega} = 0,$$

which in this case ($v_{0r} = 0$, $\partial p_0/\partial \xi \neq 0$) is equivalent to the requirement that pressure along the projection of the streamline on a plane perpendicular to the cylinder axis be constant.

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INDUCED FLUCTUATIONS OF THE INTENSITY OF RADIATION EXCITED BY AN ELECTRON BEAM IN A FLOW OF RAREFIED GAS WITH CLUSTERS

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The presence of fluctuations in the intensity of radiation excited by electrons in a jet core was discovered using an electron beam and by studying the interaction of two low-density supersonic CO_2 flows. The nature of the variation of the frequency and amplitude of the surges within the jet core as well as the region within which the surges exist depend on the parameters of the flow retardation.

The use of an electron beam for diagnostics of flows of rarefied gas has become widespread in experimental gasdynamic studies because of the fact that these methods result in quantitative data on gas density and the concentration of components and their energy states both in the quiescent and in the moving gas [1, 2]. Measurements were based on the ability to establish a unique relation between the intensity and nature of the spectrum excited by the electron beam, and the state of the gas. In this work, low-frequency radiation fluctuations in the zone of an electron beam used for probing interacting flows of rarefied gas containing clusters are studied.

This phenomenon has been studied for the interaction of two CO_2 slipstreams in a vacuum chamber. A gas-driven source with a supersonic nozzle (critical cross-section diameter $d_* = 0.53$ mm, section diameter $d = 1.22$ mm) or with a sonic nozzle ($d_* = 0.33$ mm) was mounted in the flow field at a distance of 1120 mm behind the nozzle with section diameter 100 mm and geometric Mach number $M_1 \approx 8$. The dimensions of the source were chosen to be 10 times several mean free paths, in order that the gas of the external slipstream streamlining the jet not be substantially influenced. The parameters of these flow conditions are indicated in

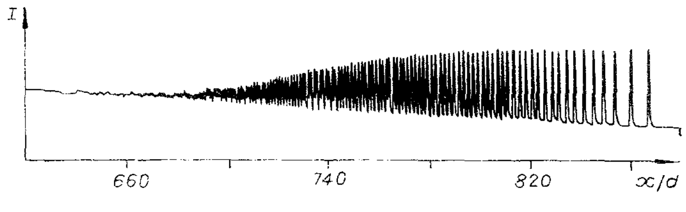

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Teknicheskoi Fiziki, No. 1, pp. 35-40, January-February, 1976. Original article submitted January 15, 1975.

TABLE 1

Regime No.	$p_{0_1}\cdot 10^5$, N/m²	T_{0_1}, K	$p_{0_2}\cdot 10^{-5}$, N/m²	T_{0_2}, K	$\left(\frac{N}{Z}\right)_1$	$\left(\frac{N}{Z}\right)_2$	M_2
1	1,18	650	13,6	330	~8	$\sim 1{,}3\cdot 10^3$	1
2	1,22	680	9,54	303	~6	$\sim 10^4$	3
3	1,18	659	4,62	308	~7	$\sim 1{,}3\cdot 10^3$	3
4	1,22	390	9,4	310	~350	$\sim 9\cdot 10^3$	3
5	1,13	410	9,26	308	~300	$\sim 9\cdot 10^3$	3
6	1,18	408	7,62	308	~300	$\sim 8\cdot 10^3$	3
7	1,3	705	9,32	308	<2	$\sim 9\cdot 10^3$	3
8	1,22	640	9,7	293	~8	$\sim 10^4$	3
9	1,24	662	0,954	323	~7	~200	3
10	—	—	9,55	288	—	$\sim 10^4$	3
11	1,17	652	3,54	330	~7	~180	1

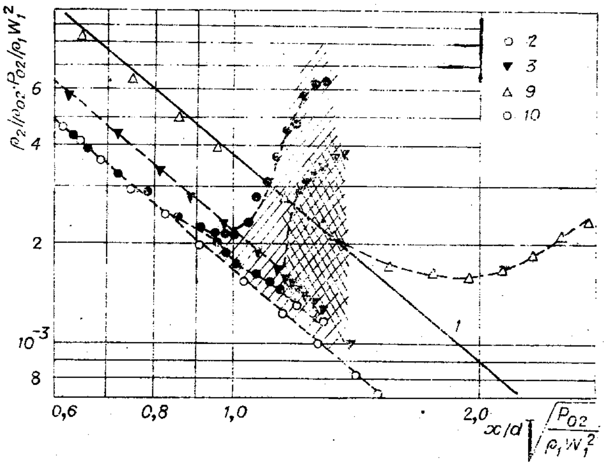

Fig. 2

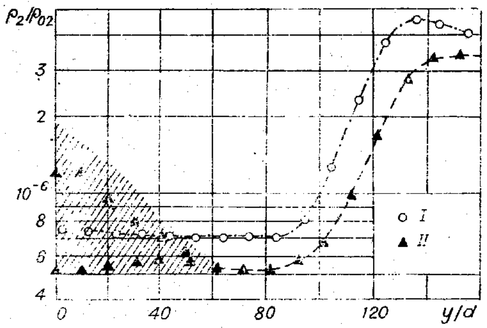

Fig. 3

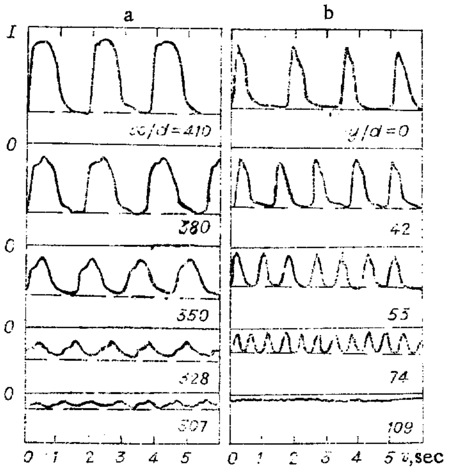

Fig. 4

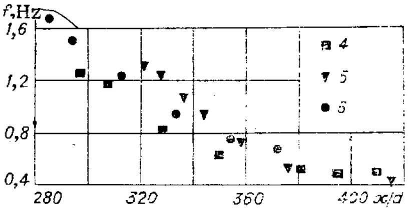

Fig. 5

Table 1. The subscript "0" denotes the retardation parameters, "1" indicating the slipstream and "2," the internal jet. Pressure in the vacuum chamber was less than 0.1 N/m^2 and did not influence the flow parameters in the region of measurement.

A beam of electrons with energies about 20 keV at a current of 0.9-1 mA was used to measure density. The electron beam permeated the entire region of interacting flows more than 1 m in diameter. Beam radiation was recorded by means of an SPM-2 monochromator with an FÉU-39 photomultiplier either on the tape of the ÉPPV-60 automatic recorder or on film of the N-700 loop oscillograph. The electron gun and optical recording apparatus remained fixed while the signal was being recorded, and the nozzle unit was shifted along the flow axis or transversely.

Fluctuations in beam glow appeared under particular conditions for both nozzles in the region of the core of the internal jet bounded by barrel shock waves. Figure 1 depicts the variation in the intensity of radiation of the gas on the jet axis 280 calibers behind the sonic nozzle (regime 1) which corresponds to a recording time of 91.6 sec. Recording was carried out using the ÉPPV-60 device with transit time of the carriage of 2.5 sec. Surges began to be discovered at a distance of 640-650 calibers from the sonic nozzle section and suddenly vanished at a distance of about 890 calibers, significantly before the zone at which the Mach disk or the X-shaped configuration become influential. A further variation in gas density (intensity of radiation) corresponds to adiabatic conditions, according to which the gas expands until surges appear. In the general case, the intensity of the signal is uniquely associated with the intensity in regions in which fluctuations are absent.

We may estimate the surge frequency with sufficient accuracy at a distance of 720 calibers. It amounts to about 1.2 Hz. It decreases far into the zone in which the surges vanish to roughly 0.18 Hz. The surge amplitudes increase with decreasing frequency and may somewhat exceed the intensity of radiation corresponding to density in free expansion. These surges are localized, as can be shown by estimates, along the jet axis in the region in the form of an ogive with cross section on the order of 10 molecule mean free paths. A similar picture for the surges also occurs in jets behind the supersonic nozzles (regimes 2-8). Regions of surges along the jet axis in regimes 2 and 3 are depicted in Fig. 2 for the density distribution in self-consistent coordinates. The lower boundary of signal variation in the surge region is denoted by darkened circles and triangles, while the broken lines depict bands of density surges. Band height corresponds to the surge amplitude. The isentropic line for $\gamma = 1.3$ and the density distribution corresponding to it in a jet in one experiment at low total pressure (regime 9) and also the density distribution in the jet core without slipstream (regime 10) are also depicted here. Surges in regimes 2 and 3 appeared at distances of about 260 calibers. No boundary of the surge zone below the flow could be detected due to limitations of the coordinate spacer displacements.

The transverse density distributions at different distances from the nozzle section were recorded in order to reveal the region within which surges appeared. Transverse density profiles for an interior jet in the section with $M_2 = 3$ (regime 8) are depicted in Fig. 3.

Density profiles at distances $x/d = 280$ and 329 calibers from the nozzle section are denoted by I and II. The first section denoted the start of the surges and the second, the region of developed surges on the jet axis. Surge amplitude fell while frequency increased as the barrel shock waves were approached (barrel shock waves were outside the zone $y/d \leq 80$ on the curve).

The ÉPPV-60 device was used to determine the surge region and to obtain qualitative data on the variation of amplitude and surge frequency. More precise characteristics as well as the shape of the signal were obtained using the N-700 loop oscillograph with a dc preamplifier having bandpass up to 20 Hz at a level of 0.7. Figure 4 depicts oscillograph recordings of the surges at points of axial (a) and transverse (b) sections of the internal jet at a distance of 438 calibers in regimes 6 and 7. Numbers indicate distances in calibers from the nozzle section and from the jet axis. The surges are asymmetric and strictly periodic. The leading edge of glow intensity surge is steeper than the trailing edge. An increase in the temperature of the slipstream (cf. Fig. 4a) leads to sharpening of the maximum of the separate surges. The separate details of the surges (nonmonotonicity of the signal history) are difficult to interpret at the time.

Data on the variation in the surge frequency along the jet axis behind the supersonic nozzle for regimes 4-6 are depicted in Fig. 5. The surge frequency measured from oscillograph data (regimes 4-6) weakly vary from regime to regime under similar conditions and vary between 1.7 Hz and 0.4 Hz along the jet. The surge frequency increased somewhat (2-0.5 Hz) in regime 7 (cf. Fig. 4b) at the highest temperature of the external flow. Anomalies in the frequency variation along the jet axis, including a sharp variation in one region or frequency invariance along a significant length of the surge zone, were observed in different regimes. Since a variation in the surges was observed along a comparatively short segment of the jet, it is difficult to establish a correlation between variations in the jet parameters and the surge frequency.

The amplitude of the surges increases downstream and reaches values 2.5-3 times greater than the values of a signal corresponding to the density at the given point. The relative amplitude falls with decreasing gas pressure.

The influence of the total slipstream temperature on the nature of the surges was specially studied in conjunction with the above investigations. It was noted that an increase in total temperature first led to a decrease in the surge amplitude with some growth in frequency and then to their total disappearance in the range of measurements at $T_{01} > 850°K$ with constant pressure P_{01}. The surges again appeared as temperature was decreased and their nature changed inversely. The region of the surges shifted downstream, basically preserving their structure as total slipstream temperature T_{01} increased and also as the total pressure of the internal jet decreased.

Thus, surges that are stably recorded under the conditions of regimes 1-8 did not arise with: a) high total pressures of the external flow; b) low total gas pressures of the internal jet; and c) in the absence of external flow. Surges were also not observed when carbon dioxide was replaced in the second (small) source by nitrogen.

The influence of a slipstream on the characteristics of surges in the core of a jet bounded by barrel shock waves can be explained by the appearance of either slipstream molecules or clusters (molecular associations) in the jet core if only one type of gas occurs in the jet and slipstream. The latter is most likely, since the interaction region of the jets is not strongly rarefied; the characteristic Knudsen number is about 0.05.

At the present time it is not possible to truly calculate the initial stage of condensation (formation of clusters) under substantially unbalanced gas expansion conditions in which the characteristic gasdynamic time is commensurate with or less than the characteristic condensation time. We may determine the order of the dimensions of clusters formed as CO_2 expands with nonequilibrium condensation. Some authors [3] have indicated that the degree of condensation in jets behind geometrically similar sources remains invariant under the similitude conditions

$$P_0 d^n = \text{const},\ P_0 T_0^{(1{,}25\gamma-0{,}5)(1-\gamma)} = \text{const},$$

for CO_2, $n = 0.6$, while $\gamma = 1.3$ for conditions at the start of cluster formation.

Values of the ratio of the number of molecules in a cluster to charge, corresponding to a given effective cluster dimension in a slipstream and in a jet, are presented in Table 1. The effective cluster dimension relative to number of molecules per charge unit in the jet core varied from roughly 200 to 10^4, and in a slipstream from monomers to 350 in the regimes studied. A surge regime with greatest amplitude corresponds to conditions of most intensive condensation (more precisely, nucleation) in internal and external flows. Fluctuations vanish when $N/Z \approx 7$ in the external flow if $N/Z \lessgtr 200$ in the internal flow. Superheating of the slipstream gas to $T_{01} \approx 850°C$, at which the surges vanish, makes condensation of the external flow impossible, that is, cluster dimension $N/Z \approx 1$.

The presence of such a correlation between the conditions for the appearance (disappearance) of clusters and the existence of surges, as well as its association with an increase in the intensity of surges of cluster growth, does not provide a direct answer to the question as to the nature of the surges.

Let us consider from the gasdynamic point of view the conditions under which surges occur. It is difficult to exactly calculate the parameters of the gas flow in nonequilibrium expansion when the adiabatic index substantially varies. Results will therefore be presented below of an estimate for gas expansion conditions.

In estimating the parameters of a slipstream we will assume that the slipstream gas expands before the nozzle section with adiabatic index 1.3 and subsequently with an index of 1.4 as a diatomic gas. The influence of the boundary layer in the nozzle is taken into account here. The interior jet and its initial section $M \approx 16$ in the region of the gas-driven source. Correspondingly, the thermodynamic mean free path is on the order of 1 mm. An internal jet with transverse dimensions more than 350 mm is a nearly solid object being streamlined. Consequently, conditions in the core of the internal jet can be estimated independently of the external flow, neglecting the influence of molecules in emergent clusters on the density distribution. Experiments have confirmed this assumption.

The mean free path of the molecules can be estimated from the thickness of the shock wave. We will use the data of Fig. 3 (regime 8). The thickness of the shock wave in the free-stream flow can be set equal, in a highly approximate way, to three mean free paths. Therefore, mean free paths of 12 and 16 mm will correspond to cross sections of 280 and 329 calibers. Similar values have been noted whenever surges have been recorded. Thus, the surge zone behind the supersonic nozzle has lateral dimensions on the order of 10 mean free paths while the longitudinal axis is on the order of 10-13 mean free paths.

Such facts as the continuous variation of the surge frequency f as the beam is shifted, noticeable within one mean free path, the positive surge amplitude (over isentropy), and the sharp cut-off of the surges at a fixed point as the beam shifts downstream make it difficult to explain the phenomenon we have discovered as purely gasdynamic.

The nature of the surges can apparently be determined by studying disturbances in the jet core due to emergent clusters and by studying the interaction of an electron beam with the clustered flow. In this case, it is necessary to consider the state of the column of plasma induced by the electron beam in order to analyze the fluctuations, since the region of the electron beam is on the average electrically neutral under typical experimental conditions.

In conclusion, the authors wish to express their appreciation to R. G. Sharafutdinov and Yu. S. Kusner for participating in the discussion of the experimental results.

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