FORMATION OF A JET OF GAS OUTFLOWING INTO EVACUATED SPACE

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Unsteady outflow from a sonic nozzle with off-design factor $4 \cdot 10^8$ at an ambient pressure of $2 \cdot 10^{-5}$ mm Hg is studied by means of the absorption of an electron beam. The motion laws of the front of the outflowing gas and other characteristic regions of the outflow are studied. A comparison to the results of other works clarifies the features of outflow with high off-design factors. An equation is obtained describing the motion of the front of outflowing gas along the flow axis. Results are presented in generalized similitude parameters.

The existence over a highly extended period of time of an unsteady structure of an outflowing jet was first experimentally established in [1, 2]. Results of these works indicated the inapplicability of calculation of ideal theory for the stabilization time of steady flow [3] and led to the necessity of a more detailed analysis of the unsteady stage of outflow, which is of definite value in many applied and research problems, including pulsing gasdynamic lasers, rocket engines, and vaporization of matter from the surface of a solid exposed to a pulsing laser beam.

Several theoretical works within the framework of various models describing unsteady flow from a source are currently known. The asymptotics of the behavior of strong discontinuities, such as an external shock wave, and interface, and a secondary shock wave at the final stage of the process for an ideal gas were considered in [4]. The different nature of the behavior of a secondary wave as a function of the stagnation temperatures of outflowing gas and the gas of the surrounding space was noted. Unsteady outflow of a viscous heat-conducting gas was considered in [5]. An approximative equation was found here for the motion of an outflowing gas front, and numerical calculations were carried out for the parameters of the flow within the framework of the Navier–Stokes equation.

The purpose of the current work is to experimentally study in detail unsteady jet flow with extremally thorough expansion. Probing by an electron beam, a method highly developed at the present time for studying steady flows of a rarefied gas, was used as the method of investigation.

The flow field for unsteady Ar outflow from a sonic nozzle with diameter $d_* = 0.25$ mm at a receiver pressure $p_0 \cong 7$ atm, and ambient pressure $p_\infty = 2 \cdot 10^{-5}$ mm Hg, and at both room stagnation temperatures of the outflowing gas and the gas of the surrounding space was investigated using the absorption of an electron beam. The motion laws for the gradient flow regions at distances up to 600 d_* along the flow axis and up to 350 d_* in a direction perpendicular to the axis was studied as a result of the investigation.

1. Description of Experiments

Experiments were carried out in the evacuated chamber of the FIRE of the Academy of Sciences of the USSR. The evacuated chamber has diameter 2.3 m, length 4.5 m, and was evacuated down to pressures of 10^{-5}-10^{-6} mm Hg using six diffusion pumps with rate above 10,000 liters/sec.

Outflow of the given gas was carried out through a sonic nozzle immediately behind a thin diaphragm that ruptured as pressure in the receiver was slowly increased to 7-8 atm. A pressure-sensitive detector

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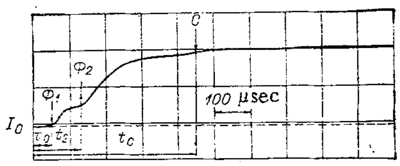

Fig. 1

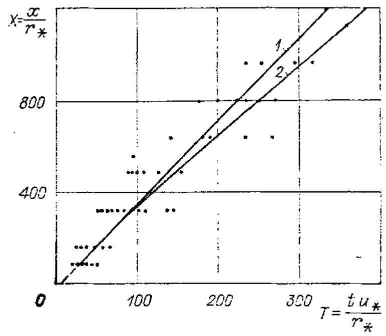

Fig. 2

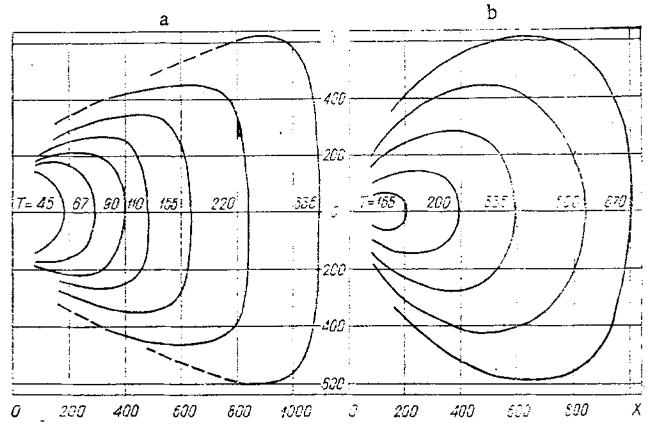

Fig. 3

that generated an electric signal at the moment the diaphragm ruptured and ensured thereby synchronization of the recording apparatus was mounted on the flange with the nozzle.

An electron beam was created by an electron beam gun* with the following parameters: electron energy 15 keV, beam current between 0.1 mA and 1 mA, beam diameter 1 mm, beam divergence $\Delta\delta$ at a length $L=50$ cm, $\Delta\delta/L \leqslant 5\cdot10^{-3}$. The electron-beam gun was placed in a reference instrument within the pressure chamber, permitting the beam to be arranged along and across the flow of the gas to be investigated. The beam passing through the flow was collected in a manifold and fed to the input of the D53A oscillograph that was triggered in synchrony with the start of outflow.

Figure 1 depicts a characteristic oscillogram for the absorption of an electron beam obtained in the experiment at the point $X=x/r_*=320$ and $Y=y/r_*=0$. The broken line corresponds to zero beam absorption. The deflection of the beam from above is proportional to the decrease in the number of electrons captured in the manifold.

The minimal distinctly different magnitude of the relative absorption amounted to $(\Delta I/I)_{min} \gtrsim 10^{-3}$ in our experiments. This corresponded to $\rho L \gtrsim 3\cdot10^{-9}$ g/cm^2, where ρ is gas density, and L is the electron-beam length in the gas, which determines for a characteristic flow dimension $L\approx10$ cm the lower limit of densities that can be recorded, $\rho_{min} \gtrsim 3\cdot10^{-10}$ g/cm^3.

Distinct absorption signals were recorded at distances between 80 and 1200 critical radii along the axis and from 80 r_* to 700 r_* along both sides of the flow axis.

Two characteristic gradients in absorption alternating with constant levels can be seen easily on the oscillogram. The time t_0 corresponds to the propagation time of the first disturbance from a nozzle section to a given point. The point Φ_2 marks the moment of arrival of the second absorption gradient and the point C, the establishment of a steady level. The time for the passage of all nonsteady structures varies from 300 μsec to 500 μsec as a function of distance from the nozzle section. A steady absorption level established at a point did not vary over the entire measurement time (up to 5 msec).

* The electron-beam gun was designed and produced to our specifications at the V. I. Lenin All-Union Electrotechnical Institute.

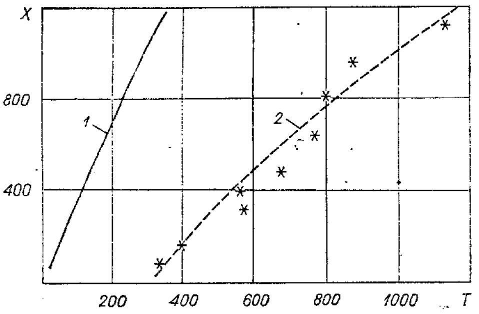

Fig. 4

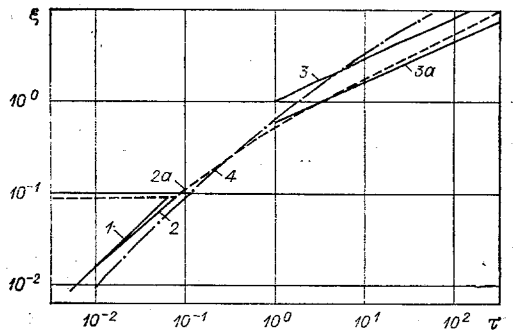

Fig. 5

2. Results of Experiments

A shock wave propagated with finite pressure before the outflowing gas front at the initial stage of outflow into space. Since the initial density in the external gas amounted to $\rho_\infty = 3 \cdot 10^{-11}$ g/cm^3 under the conditions of our experiment, this outer shock wave, leading to no more than a fourfold rise in density in Ar, could not produce a density increase above the sensitivity threshold. Therefore, all the registered absorption signals corresponded to an increase in density in outflowing gas. The moment Φ_1 on the oscillation (cf. Fig. 1) is identified with the arrival of the outflowing gas front at a given point in space.

Figure 2 depicts experimental results of a time dependence for the propagation of an outflowing gas front along the flow axis. The dimensionless coordinates $T = tu_*/r_*$ and $X = x/r_*$, where r_* and u_* are the critical radius and speed of sound, are laid out along the axes.

Empirical approximations of the motion equations for an outflowing gas front were determined by the method of least squares, taking into account the dependence of the dispersion of time T on coordinate X. Dispersion varied with increasing X in proportion to X^2. This fact is due to an increase in the scatter of the experimental points, resulting from a drop in sensitivity of the method as density decreased with distance from the nozzle section, and also irregularity in the flow, which are highly distinct, for example in the Schlieren photographs given in [1, 2].

We obtained for the form of the motion equation with arbitrary exponent used in [2], the equation

$$T = 6.6 + 0.18X^{1.06}, \tag{2.1}$$

which corresponds to curve 1 in Fig. 2.

For a weighted regression in the form of a quadratic trinomial, we found (curve 2, Fig. 2)

$$T = 6.6 + 0.25X + 6.6 \cdot 10^{-5}X^2. \tag{2.2}$$

The free term in Eqs. (2.1) and (2.2) is apparently due to outflow lag and will subsequently be omitted.

Statistical analysis of the data allow us to conclude that the approximation of Eq. (2.2) is legitimate with 99% reliability and that the quadratic term will be significant for degree of significance $\alpha = 0.3$ (i.e., the coefficient of the quadratic term is nonzero with 70% confidence probability). A confidence interval was also determined for the curve of the regression in Eq. (2.2). For example, values of arrival time T for the front of the gas with corresponding 70% confidence intervals were obtained at the points $X_1 = 320$ and $X_2 = 560$:

$$T(X_1) = 83 \pm 16; \quad T(X_2) = 155 \pm 56.$$

The nature of the variation in the speed of the outflowing gas front was determined on the basis of the motion equation (2.2). It varied from 1100 m/sec to 800 m/sec along the axis at distances x from 80 r_* to 1200 r_*.

An analysis of the data obtained at peripheral points permitted the general pattern of the spatial propagation of the front to be determined. Curves for the position of the outflowing gas front in coordinates X and Y at distinct moments of time T carried out by averaging the experimental data are depicted in Fig. 3a. It can be seen that the spherical symmetry of the flow (about the center of the nozzle) is violated quite early, at times on the order of 30 characteristic values and distances on the order of 200 r_*. Axial symmetry of the flow subsequently becomes highly influential and the leading edge flattens out. We should note, however, that the curves in Fig. 3 characterize propagation of gas with density at least that of the limit of sensitivity, which does not exclude the possibility for gas of lower density to enter peripheral regions.

Propagation of the second absorption gradient and the moment at which the steady level is attained is of a less regular nature. Therefore analytic treatment of the motion of these flow regions was not carried out and only the qualitative nture of their propagation was considered.

The spatial propagation of the second absorption gradient is depicted in Fig. 3b. It is evident that spherical symmetry is violated in this case beginning with the very initial outflowing stages. The curves of Fig. 3, in addition, cannot be considered as equal density curves since they correspond to equal interval absorption levels, i.e., they characterize the interval density along the path of the beam.

Figure 4 depicts the experimental dependence for the propagation of the transient time of steady absorption on time along the axis (curve 2). Values averaged over data from 6-8 tests are indicated by stars. Curve 1 in Fig. 4 depicts the motion of the front of outflowing gas.

3. Analysis of Results

It is necessary to use generalized parameters, taking into account not only the scale size of the nozzle, but also characterizing gas expansion in the flow in order to generalize the results obtained and to compare them with data for other conditions and results of calculations. Such parameters suitable for describing the initial flow stage from a source were proposed in [5].

Figure 5 depicts the motion of the front of outflowing gas in parameters ξ and τ:

$$\xi = x/r_* \sqrt{\rho_\infty/\rho_*};$$
$$\tau = t/t_* \sqrt{\rho_\infty/\rho_*},$$

where $t_* = r_* / u_{\max}$; $u_{\max} = 2/(\gamma-1)a_T$; ρ_* is critical density. Curves 1 and 2 correspond to Eqs. (2.1) and (2.2),

$$\tau = 0.84\xi^{1.06}, \tag{3.1}$$

$$\tau = 0.6\xi + 2.7\xi^2. \tag{3.2}$$

The maximal value of ξ in these experiments is indicated by the broken horizontal line. Curve 2 represents the motion of the front of outflowing gas in experiments* from [2]

$$\tau = \xi^{1.92}. \tag{3.3}$$

The difference in the ranges of variation in the parameters ξ and τ illustrate the difference in the physical condition of expansion in our experiments and those of [2].

The dot-dashed line 4 is the calculated motion equation for the front obtained on the basis of [5],

$$\tau = \xi + 0.46\xi^2.$$

The asymptotics of this motion equation, considered in [5], indicate that the quadratic term becomes substantial with noticeable counterpressure of the surrounding gas. Motion of the front is approximately described by a linear law at earlier expansion stages or for outflow into a vacuum. This is well confirmed by the experimental data. Thus a comparison of Eqs. (3.3) and (3.1) indicates roughly quadratic law ($\tau \sim \xi^{1.92}$) when $\xi \leq 1$ and its approximation to linear form ($\tau \sim \xi^{1.06}$) when $\xi < 10^{-1}$.

It is also evident for a motion equation in the form of a quadratic binomial (3.2) that the linear term noticeably exceeds the quadratic term over the entire range of our experimental data. Extrapolation of this motion equation for the front to larger parameters indicates that the effective exponent in Eqs. (3.2) and (3.3) coincide when $\xi > 1$, which indicates the definite value of counterpressure at this flow stage.

The understatement in the experimental value of the rate when $\xi > 1$ in comparison with calculations for a source may be due to flow energy losses from eddy motion, which is highly noticeable in all the Schlieren photographs from [2]. Eddy motion in our experiments may be the cause of the large scatter in the nature of motion and in the amplitude of the second absorption gradient.

*Ar outflow from a sonic nozzle 4 mm in diameter at $p_0 \simeq 1$ atm, $p_\infty = 13$ mm Hg, and $T_0 = 2000$°K was considered.

If we generalize the results on the motion of an outflowing gas front and take into account the temperature factor T_∞/T_*, the experimental values from [2] turn out to agree well with the dependence obtained by extrapolation of the results of our work (curve 3a and the broken curve 2a of Fig. 5).

A secondary shock wave is one more region where density sharply varies and characterizes the structure of unsteady outflow. A secondary shock wave was formed and observed directly from the nozzle section in [1, 2] when forming jets in space with comparatively high counterpressure. In this work a secondary shock wave was not recorded over the entire period of observation for low p_∞.

LITERATURE CITED

1. I. M. Naboko, T. V. Barhenova, A. I. Opara, and V. A. Belavin, "Formation of a jet of shock-heated gas outflowing into evacuated space," Astronaut. Acta, 17, 653-659 (1972).
2. V. A. Belavin, V. V. Golub, I. M. Naboko, and A. I. Opara, "Investigation of nonsteady flow structure with outflow of shock-heated gas," Zh. Prikl. Mekh. Tekh. Fiz., No. 5, 34-40 (1973).
3. V. P. Gusev, "Triggering supersonic nozzles," Inzh. Zh., No. 1 (1961).
4. G. A. Simons, "The large time behavior of a steady spherical source expanding into an arbitrary ambient gas," AIAA Paper, No. 70, 232 (1970).
5. S. F. Chekmarev, "Nonsteady-state radial gas expansion into a flooded space from a suddenly switched on stationary source", Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1975).