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INVESTIGATION OF FLOW IN THE CHAMBER AND CHANNEL OF A VARIABLE-AREA SHOCK TUBE

A. M. Naumov and L. S. Shtemenko

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One factor which affects the flow uniformity in a shock tube is the noninstantaneous nature of the diaphragm-opening process. Several investigators [1, 2] have calculated the flow in a shock tube channel in one-dimensional formulation, allowing for this factor.

In this paper the problem is considered two-dimensionally. The flow parameters were calculated on a BÉSM-6 computer using the Lax–Wendroff numerical method. The following dimensionless parameters were used: D is the semidiameter of the tube; p_0, ρ_0 are the initial pressure and density in the shock tube channel; $\sqrt{p_0/\rho_0}$ is the characteristic velocity; and $D/\sqrt{p_0/\rho_0}$ is the characteristic time. The gas is taken to be inviscid, non-heat-conducting, with constant specific heat ratio $\varkappa$. The governing parameters of the problem are

$$P = p_1/p_0;\ R = \rho_1/\rho_0;\ \varkappa;\ t_*$$

(t_* is the dimensionless diaphragm opening time). The subscripts 0 and 1 denote the gas parameters to the right and left of the diaphragm.

The two-step Lax–Wendroff method used here is based on a difference approximation to the Euler equations of motion, written in divergent form. The smoothing introduced for strong detonations [3] allows us to avoid the characteristic oscillation of the solution. The method has second-order accuracy and affords a continuous computation of the flow field without isolating strong discontinuities. In the shock tube sections with curved boundaries the transition to a design field of rectangular shape is accomplished by the coordinate transformation

$$X = x;\ Y = y/y_c(x),$$

where $y_c(x)$ is the function giving the wall shape.

The structure of the equations of motion does not vary, but the new dependent variables differ from the old by factors which depend on the channel shape [4]. The flow field is covered by a rectangular mesh. To calculate the flow parameters at each node we deal with a nine-point cell, having the node to be considered at its center.

For the computations the flow in the tube with the diaphragm is modeled as follows. The diaphragm is replaced by a transverse membrane of zero thickness, separating the gases with different initial parameters. At time $t = 0$ the membrane begins to open from the center to the walls according to a given time law. The presence of the membrane requires a nonpermeability condition, similar to the channel walls. The nonpermeability condition is achieved by means of a fictitious flow which, interacting with the computed flow, makes the normal velocity component zéro at the points on the solid boundary. In order to satisfy the boundary condition on the moving membrane, the calculation uses two columns of points spanning the membrane. The flow parameters at pairs of points are distinct as long as the membrane separates them. When this is not true identical values are given to each, and the point pairs are regarded as a single point. For this reason the relative position of the ends of the opening membrane and the computational cell belonging to it are analyzed

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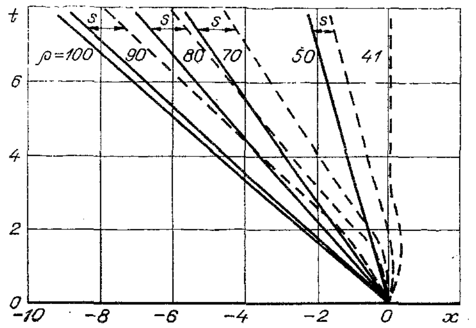

Fig. 1

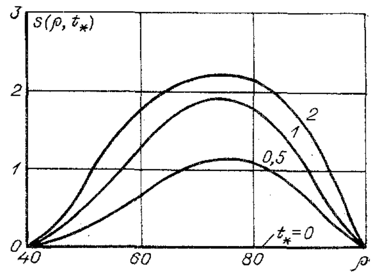

Fig. 2

at each time step. Depending on the result the required computational version is selected. An estimate of the results obtained using simple averaging and the formulas for decay of an arbitrary discontinuity at the point pairs on the diaphragm showed that the results obtained for each of the versions differed insignificantly. This allowed us to use the first version in order to reduce the computational time. With this objective the calculation is made only for the disturbed part of the field at each time step. It is assumed in the calculations that the diaphragm opens according to the law given in [1], which is in satisfactory agreement with known experimental data. Because of flow symmetry only one half of the tube is considered, and the condition is applied that no flow passes across the axis, like the condition for solid boundaries. It was established in [5], by comparing computed results for a constant area tube with the exact solution, for instantaneous diaphragm opening, and with experimental data, that the flow model adopted with noninstantaneous diaphragm opening is valid.

It is known that the expansion waves excited in a shock tube during noninstantaneous opening are not centered and are nonplanar in shape for a time comparable with the diaphragm opening time [6]. To examine this difference, calculations were made for a planar flow with the following values of the governing parameters: $P = 100$; $R = 100$; $\varkappa = 1.4$; $t_* = 0$, 0.5, 1, 2.

Figure 1 shows the trajectories of points in an expansion wave with constant flow parameters at $t_* = 2$. The results correspond to the axis of symmetry; Fig. 1 also shows the straight-line characteristics of a centered wave, corresponding to the same values of the flow parameters. It can be seen that, beginning at a certain time, the lines corresponding to the same values of density have the same slope, but have a relative displacement. The straight parts of the lines are given in this case by the relation

$$(x - s)/t = u(\varkappa + 1)/2 - a,$$

where s is the displacement of a particle having the velocity u at the point x, t from its position in the centered expansion wave; and a is the speed of sound in the gas at rest. Figure 2 shows a graph of the relation $s = s(\rho, t_*)$ for various values of t_*. Knowing this relation we can determine the flow in an expansion wave in the shock tube chamber in the actual case.

To verify the computational method, and also to elucidate the wave flow picture in a variable area shock tube (Fig. 3a), calculations were performed for a tube configuration with the following values of the governing parameters: $P = 19$; $R = 19$; $\varkappa = 1.4$; $t_* = 3.8$.

Figure 3b shows the field of isobars corresponding to the time when the perturbations from the opening diaphragm have reached the nozzle throat. The location of the greatest bunching of the lines corresponds to the presence of large pressure gradients in the secondary discontinuity generated by overexpansion of the gas in the supersonic jet discharging through the diaphragm aperture and in the compression waves incident and reflected from the convergent part of the nozzle. The range of pressure variation in the isobars is 0-5. The dashed lines here show the position of waves obtained experimentally by the holograph method in the shock tube at the Department of Molecular Physics and Mechanics at Moscow State University (MGU). In these tests shaped inserts coinciding in shape with the configurations used in the calculations were mounted on the walls of a rectangular section shock tube at a distance of several diameters from the diaphragm. The values of the governing parameters were kept constant. The layout of the holographic equipment is described in [7]. Figure 3c, d show photographs, as an example, of the virtual image of the flow wave picture in the nozzle, obtained from holograms with different angles of observation. In the photographs one can easily see reflection of the forward shock from the convergent part of the nozzle.

In the isobar fields shown in Fig. 4 one can see the motion of the forward shock wave, the formation of compression waves from the convergent part of the nozzle, the interaction of these with the secondary

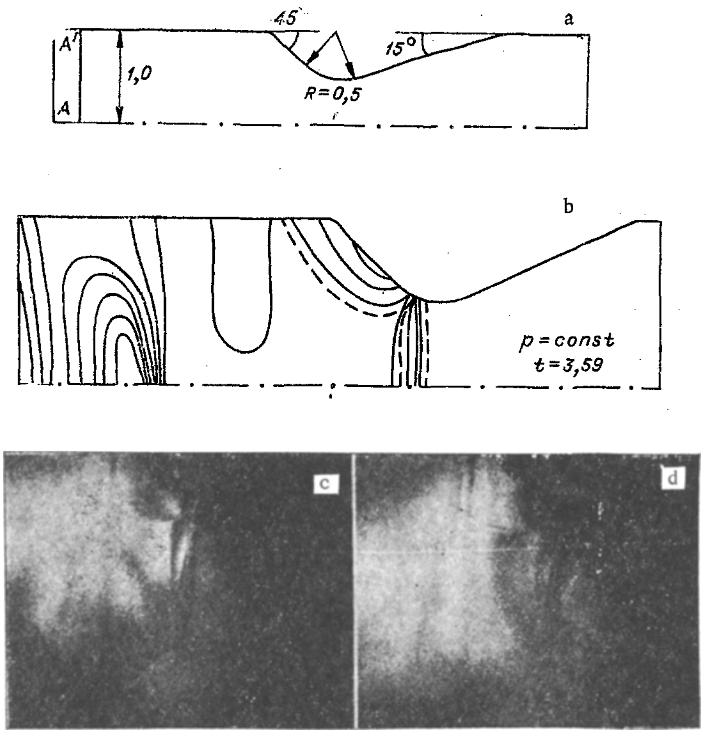

Fig. 3

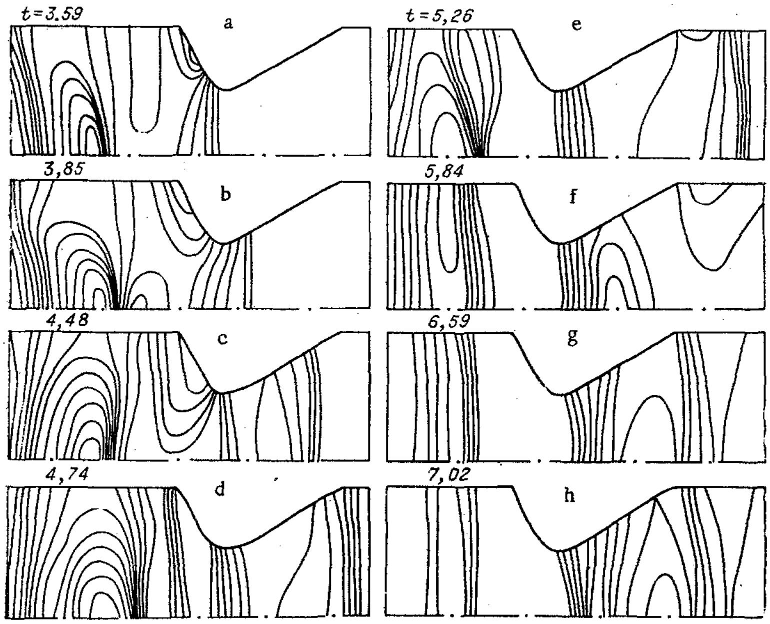

Fig. 4

shock (Fig. 4a–e), the generation of an internal shock due to overexpansion of the gas in the expanding part of the nozzle (Fig. 4f–h), and the generation of compression waves in the corner flow at the nozzle exit (Fig. 4e–h).

The satisfactory agreement between the computed and the experimental data is evidence that one can use this computational technique to solve non-steady-state gasdynamic problems related to the construction and operation of short-duration aerodynamic facilities.

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A METHOD OF DETERMINING THE PERFORMANCE OF LOW-DENSITY GASDYNAMIC TUBES

S. N. Abrosimov and B. F. Shcherbakov

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The parameter describing the efficiency of a gas-pumping system is the rate or pumping speed. In contemporary vacuum pumps this parameter can have quite high values, e.g., vapor-jet pumps having pumping speed ~15,000 liter/sec and higher at pressures of 10^{-3}–10^{-4} torr [1, 2], while cryogenic pumps have values of 10^6–10^8 liter/sec at the same pressures [3-5]. With these parameters the gas-flow rate per second under steady conditions can be as high as tens of grams. To determine the performance of gas-pumping systems one usually must measure a considerable number of parameters. Here we propose a method of determining the performance from the geometrical dimensions of the jet flow, based on the fact that the gas-flow rates through the nozzle and through the pumping system are equal. The gas-flow rate through a nozzle can be written in the form

$$G_c = \mu A(k) F_* p_0/(RT_0)^{0.5}, \qquad (1)$$

where μ is the mass-flow coefficient (in many cases we can assume this to be 1 for simplicity); $A(k) = [2/(k+1)]^{1/(k-1)}[2gk/(k+1)]^{0.5}$ is the discharge coefficient; $k = c_p/c_V$ is the specific-heat ratio; F_* is the nozzle throat area; p_0 and T_0 are the stagnation pressure and temperature, respectively; and R is the gas constant.

The gas flow rate through a pumping system can be expressed in the form

$$C_{\text{pump}} = S\gamma p_\infty/p_\gamma, \qquad (2)$$

where S is the efficiency; γ is the specific weight; p_∞ is the pressure in the working volume, created by the pumping system; and p_γ is the pressure at which the specific weight is determined.

Then, from equality of Eqs. (1) and (2), we obtain the expression

$$S = \frac{A(k)\,\pi r_*^2 p_0 p_\gamma}{(RT_0)^{0.5}\,\gamma p_\infty}, \qquad (3)$$

which is a starting point for determining the performance of the pumping system. It is known [6-8] that the geometric dimensions both longitudinal and transverse, of jets discharging into a rarefied volume, depend on the degree of expansion of the gas flow p_0/p_∞. The quantity that can be most conveniently measured is the distance along the jet axis from the nozzle throat to the point of minimum total pressure, corresponding to the position of the Mach disk. The measurement is carried out by a very simple total pressure sensor, for which the measurement technique is well developed. It is also possible to determine the position of the Mach disk by some other method (e.g., by visualizing "cold" jet flows by the "glow discharge" or the electron-beam method, and also to record parameters such as the density or the static pressure).

For a wide range of expansion of the gas flow (Fig. 1, solid line), the distance from the Mach disk x_m at Knudsen $Kn_{0,d*}(p_0/p_\infty)^{0.5} < 2 \cdot 10^{-3}$ is $x_m = 1.35\,(p_0/p_\infty)^{0.5}\,r_*$.

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