Journal of Engineering Physics and Thermophysics, Vol. 68, No. 4, 1995

CALCULATION OF THE PROCESS OF BLAST WAVE DIFFRACTION IN A CYLINDRICAL CHANNEL

V. A. Andrushchenko and M. V. Meshcheryakov UDC 533.6.011.72

We performed a numerical investigation of the process of transition of a spherical leading front into a plane one in a cylindrical channel. The processes of the collision of reflected shock waves, formation of a nonstationary grating-like structure of flow, and of the overtaking interaction of shock waves are investigated. We found that in the presence of hot gas layers on the walls of the channel a plane head front is not formed.

Special features of the development of explosion processes in closed and half-closed spaces were investigated in both experimental [1, 2] and theoretical works [3]. We obtained empirical dependences of the parameters of shock waves (SW) in tubes valid at large distances from the center of explosion, over which one can neglect the piston action of its products; in this case a spherical shock wave is transformed into a plane one. In [2] the near zone of explosion was also investigated experimentally.

Below we present the results of calculations of a spherical explosion in a channel in the axisymmetric formulation for the parameters of a SW, close to those specified in experiments [2], as well as the results of numerical investigation of the problem for the case where there are layers of a hot gas of different thicknesses and temperatures on the walls of the channel. Interest in such a problem is associated with the well-known warping effects of the front of a radiating SW propagating in a channel [4]. Experimental investigation of such a phenomenon is presented in [5]. The interaction of a spherical shock wave with a plane covered with a hot gas layer was investigated numerically in [6] where the main phases of this unsteady-state flow were investigated. In [7] an assumption was made about the self-similarity of the flow induced in the interaction of a plane SW with a thermal layer.

In the present work (except for one calculation) we consider the problem of explosion between two parallel planes in the presence and absence of hot gas layers.

The mathematical statement of the problem coincides with that given in [6], except for the fact that a rigid surface is presented by both the plane $z = 0$ and the plane $z = 2.4$ (the z axis is the axis of symmetry). As a mathematical model we selected a full set of nonstationary Navier-Stokes equations for a compressible heat conducting gas with constant coefficients of transfer [see [8]). The set of equations is written in a cylindrical coordinate system (r, z). The initial system of differential equations is approximated by a difference system with the use of an implicit difference scheme of splitting into functions and coordinate directions [8]. As the initial data for the explosion parameters we assigned the tabulated distributions of pressure, velocity, and temperature for a point explosion in a medium with a back pressure. In this case the initial dimensionless pressure at the SW front was selected to be equal to $p_f = 2.1$ (the Mach number M = 1.4), while the distances between the planes a' were equal to 3 and 3.8 cm in correspondence with the experimental data of [2].

First, we consider the problem of the diffraction of a blast SW between two parallel planes in the absence of layers of a hot gas on them. The governing dimensionless parameters of the problem are

$$\mathrm{Re} = 10^3 ; \quad \mathrm{Pr} = 1 ; \quad \gamma = 1.4 ;$$
$$a = a' R_0 = 2.4 \quad (\text{and} \quad 3.04) ; \quad p = p_f\, p_0 = 2.1 . \tag{1}$$

Department of Theoretical Problems of the Russian Academy of Sciences, Moscow Physicotechnical Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 4, pp. 583-588, July-August, 1995. Original article submitted December 29, 1993.

 1062-0125/95/6804-0476$12.50 ©1996 Plenum Publishing Corporation

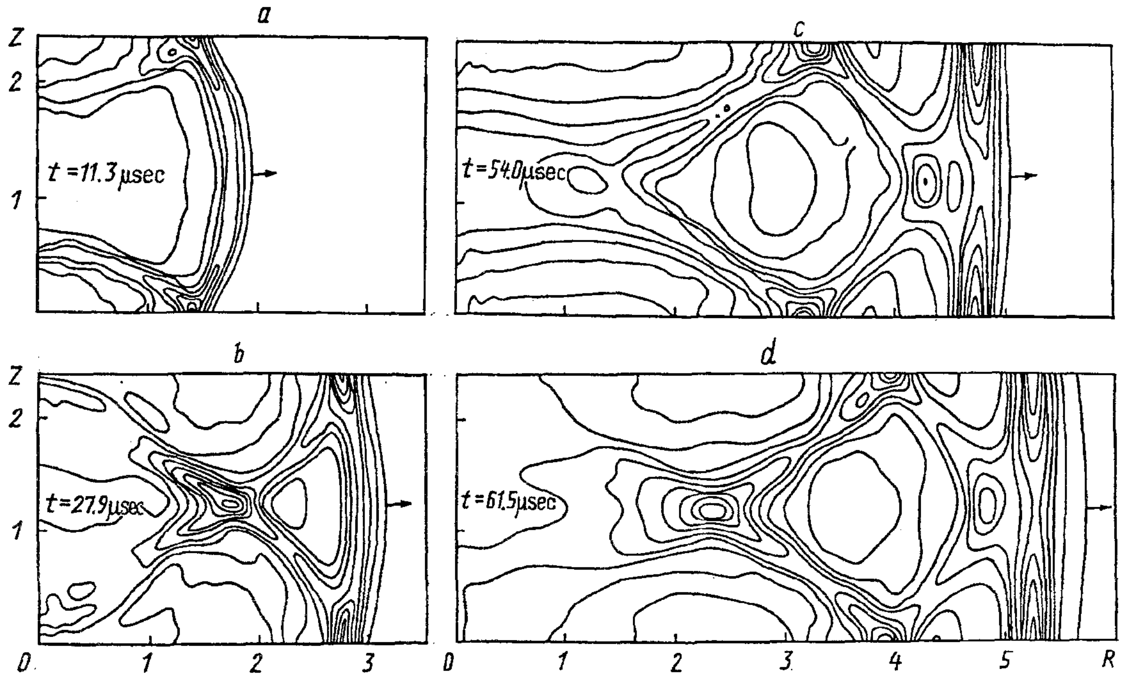

Fig. 1. Two-dimensional structure of flow with diffraction of a spherical shock wave between parallel planes (isobars).

Here, R_0 is the initial radius of the blast wave (R_0 = 1.25 cm), p_0 is the pressure in the nonperturbed medium. The technique of making the remaining gas dynamic variables nondimensional is presented in [8].

When a SW propagates in such a half-closed space, the energy of the SW is scattered much more slowly than in an unbounded space. In this case the intensity of the SW is determined not only by the initial energy of explosion, but also by the processes of reflection (thus, an additional parameter appears, namely, the coefficient of friction of air against the channel surface). We note that in a given case the center of explosion is located at an equal distance between the planes (the results of calculations for the case where this condition is violated will also be considered below). As a result, the flow pattern remains symmetrical with respect to the central plane at all times; taking this symmetry into account, the process of the diffraction of a SW between two planes is completely analogous to the reflection of a SW from one plane, but only up to the start of interaction of the waves reflected from the plane (see Fig. 1a which shows the pattern of isobars in the rz plane up to the moment of collision of the reflected waves). For the parameters prescribed in the calculations, the collision of the SW occurs at t = 15 μsec (the moment t = 0 is considered to be the moment with the initial distribution of the parameters of the SW: $p^*(r, z)$, $u^*(r, z)$, $v^*(r, z)$, $T^*(r, z)$ at $p_f = 2.1$ (see [9]). In the process of collision of the reflected waves a cumulative effect is realized that leads to a rise in pressure in the region of contact (at the point with coordinates $r = 0$, $z = 1.2$ the pressure increases from 1.1 to 1.3); moreover, a complex structure of irregular reflection is formed here that has the form of a "hanging" compression shock on the pattern of isobars (see Fig. 1b). The shock formed starts to move along the middle plane $z = 1.2$ in the direction of the leading front. Similar phenomena appearing on interaction of reflected waves were investigated numerically in [8]. The specific feature of the present problem is that the collision occurs in a hot central zone of explosion and the leading fronts of the reflected waves have already been deformed because of the formation of precursors. (The mechanism of the interaction of a blast shock wave with the spherical region of a hot gas is detailed in [10].) From Fig. 1b (t = 27.9 μsec) it is seen that transition from regular to Mach reflection occurs in the head wave, there is a hanging shock in the axial zone, and the reflected waves arrive at the opposite planes. The configuration presented in this figure is the first phase of a nonstationary grating-like structure, which is realized in a given flow. Because of the above-noted cumulative effect, the values of pressure and velocity in the hanging shock are maximum in the flow (thus, at t = 27.9 μsec $p = 1.45$ and $u = 0.3$ in the shock, and in the Mach wave of the leading front $p_f = 1.3$ and $u_f = 0.22$). As a result, the shock gradually overtakes the leading front (deformation and compression of the first mesh of the grating-like structure occurs). In

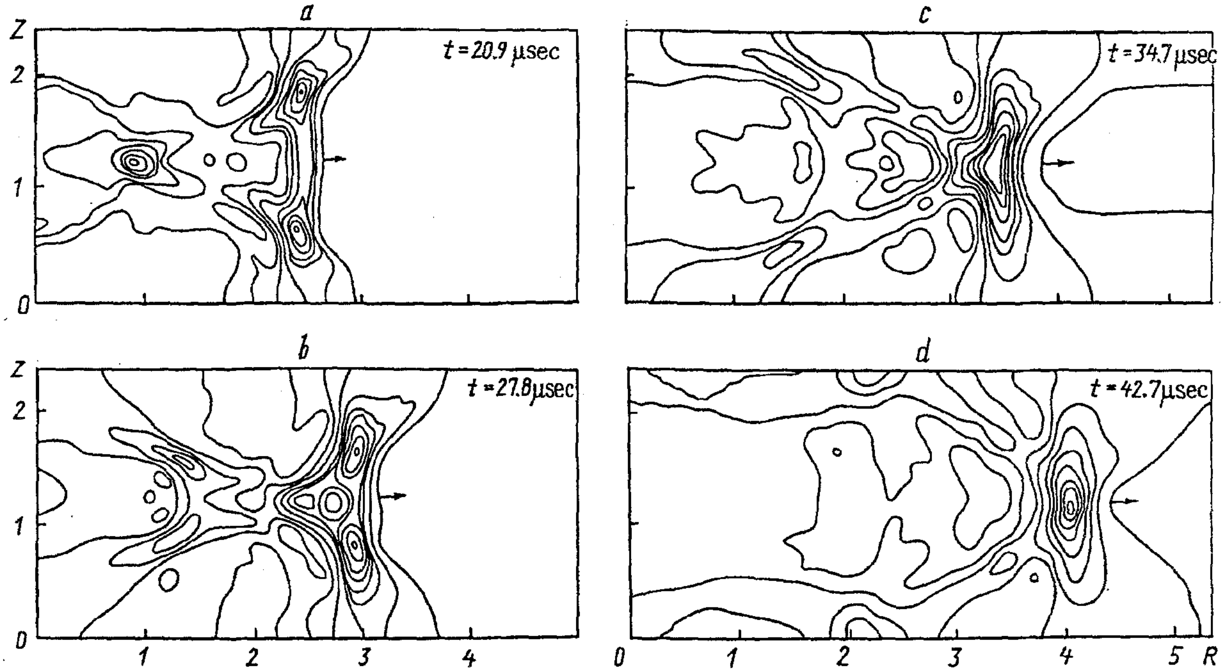

Fig. 2. Flow structure in the presence of hot gas layers with equal temperatures of 1000 K on the planes of the layers (isobars). Dimensionless values of coordinates are indicated along the R and Z axes.

Fig. 1c (t = 54 μsec) we already see a virtually formed plane leading front (in the formulation considered, it is, strictly speaking, a straight front of a cylindrical shock wave) in which the Mach waves, coming from the upper and lower planes, merge with the axial shock. Moreover, in this figure we see the onset of a new Mach structure on secondary reflection of a SW, as well as the beginning of the interaction of this secondary reflected wave in the axial zone. In Fig. 1d (t = 61.5 μsec) we see just another shock formed in the axial zone also with a cumulative effect, followed by its overtaking interaction with the leading front.

Thus, as a result of the calculations, we investigated in detail the mechanism of the formation of a straight leading front on diffraction of a blast SW between two planes (a plane front on explosion in a channel). We managed to reveal certain new characteristic features of the flow: the formation of a nonstationary grating-like structure behind the leading front, the phenomenon of the overtaking interaction of axial hanging shocks with the leading front, as well as of secondary Mach structures that gradually overtake the leading front. In [2, 3] it was found that the zone of formation of the plane front L attains 4-8 characteristic radii of the channel. In calculations we obtained $L \simeq 4.5b$ (where $b = a/2$ is the half-distance between the planes), which corresponds to the experimental result from [2], where $L \simeq 4.7r$ (r is the radius of the cylindrical channel).

When the center of explosion is not located in the middle plane, diffraction processes on the whole develop in a qualitatively similar manner. However, the violation of symmetry leads to both a change in the intensities of the interacting secondary SWs and the ultimate formation not of a straight, but rather of an oblique, leading front (the slope is to the side of the plane to which the center of explosion is closer).

We consider now the results of the calculations, where the thermal layers of the hot gas are located near the planes (version 1: $h_1' = h_2' = 0.2R_0$ and $T_1' = T_2' = 1000$ K).

Thus, the determining parameters listed in (1) are supplemented with four new parameters: $h_1 = h_1'/R_0 = 0.2$; $h_2 = h_2'/R_0 = 0.2$; $T_1 = T_1'/T_0 \simeq 3.5$; $T_2 = T_2'/T_0 \simeq 3.5$. (Here $T_0 = 288$ K is the temperature of the nonperturbed medium.)

The presence of a thermal layer (TL) leads to a qualitative rearrangement of the structure of flow in the channel (for further details on the specific features of the interaction of a blast wave with a TL and a plane see [6, 9]). The presence of a TL promotes earlier reflection of the SW from the plane (though with smaller intensity). Thus, in Fig. 2a (t = 20.9 μsec) the reflected waves have already interacted between themselves with the formation of a hanging shock. Moreover, in this very figure we see hanging shocks and precursors formed in the head structure (near the upper and lower planes). As precursors develop, they gradually come closer together (compare Fig. 2b with Fig. 1b for the same time moment). In Fig. 2c we see that all three hanging shocks merge into one. In this case grating-like structures are not formed from secondary reflected waves, since they are greatly weakened in the thermal layers and virtually cannot be identified. It is seen in Fig. 2d ($t = 42.7$ μsec) that the leading front consists of two wedge-shaped precursors and a single hanging shock in the region of the middle plane. Thus, the presence of a TL (on the channel walls) prevents the formation of a plane leading front and of a periodic wave structure in the rear flow.

We will consider now the case where the temperature of the lower layer is equal to $T_1 = 3500$ K. In spite of the fact that the center of the explosion is located in the middle plane, the difference in the temperatures of the layers leads to the violation of symmetry of the flow. In this case the unified shock originates above the middle plane, and thereafter its trajectory represents a sinusoidal curve near the middle cross section; in vertical dimensions it elongates along the z axis, gradually occupying the entire cross section between the planes.

Of some interest are also the results of calculation of still another variant, when the center of explosion is located in the middle plane, the thermal layer with $T_1 = 100$ K is at the bottom, and there is no layer at the top, i.e., $T_2 = T_0 = 288$ K. In this case the hanging shocks (one above the lower thermal layer, the other at the central zone of the intersection of reflected waves) merge at time $t = 30$ μsec, and the unified shock moves in the direction of the upper plane together with the growth of the precursor, gradually absorbing the Mach wave near the upper plane. The head configuration at the late stages of flow ($t = 70$ μsec) represents an oblique inclined front (this is the precursor spread over the entire space).

On building of the wall layer of hot gas due to the radiation of the SW, the layer thickness will be substantially smaller than that prescribed in the calculations, and its influence on the flow will be exerted at later time moments. Nevertheless, this problem confirms that the thermal layer may change the flow structure in principle.

For practical applications [11] it is interesting to calculate such flows in more complex half-closed channels containing different kinds of partitions in the cross section. Such flows can lead to destruction of the formed plane front due to the problem geometry and its subsequent reconstruction.

The above calculations were performed on an ES-1055M electronic computer with the use of difference 250 × 120 grids (in the direction of the r axis the number of nodes was increased with propagation of the SW). Control of the accuracy was made by observing the fulfillment of the momentum and energy conservation laws, as well as by investigating the convergence of the solution on the grid. One variant of computation required 20–25 h of computer time. Comparison of the results of calculations for the change of excess pressure, specific momentum of excess pressure, and the time of the compression phase with the empirical formulas given in [3] for straight channels of constant cross section gave good agreement (within 10%).

We note that using the selected values of the governing parameters ($Re = 10^3$ and $Pr = 1$) and the model used in the calculations, and invoking the Navier-Stokes equations, we obtain results that are close to those obtained using an inviscid model. This is explained by the fact that in a given case the "physical" viscosity has the order of schematic viscosity, and the viscous terms in the equations of motion and in the equation for temperature can be considered as a specified artificial viscosity. This problem is discussed in more detail in [9]. The heat conduction effects in this problem manifest themselves weakly due to the very small characteristic times of the processes – of the order of tens of microseconds. However, the numerical model used was developed for investigating the widest possible class of physical phenomena, including those, in which the role of viscosity and thermal conductivity is substantial.

In conclusion we note that the results of the calculations presented in this work were considered from the viewpoint of maximum possible comparison with available experimental data, and therefore considerable attention was paid to the problem of a symmetrically located center of explosion, since experimental results are available only for this formulation. In the case of nonsymmetric location of explosion, and also in the presence of thermal layers with different temperatures, a very large number of dimensionless governing parameters appear in the problem. A more detailed study of the possible originating flows is the subject of further investigations.

NOTATION

r, z, radial and axial coordinates; t, time; p, pressure; T, temperature; u, v, radial and axial velocity components; a, distance between the planes; b, half-distance between the planes; d, channel diameter (in experimental data); R_0, initial radius of the shock wave front; $p^*(r, z)$, $u^*(r, z)$, $v^*(r, z)$, $T^*(r, z)$, distributions of pressure, radial, and axial velocity, and temperature at the initial time moment; L, length of the zone of formation of a plane front; T_1, T_2, temperature of gas in the lower and upper thermal layers; h_1, h_2, thicknesses of the lower and upper thermal layers.

REFERENCES

1. S. D. Savrov and I. M. Ageev, Teplofiz. Vys. Temp., 18, No. 6, 1257-1262 (1980).
2. É. K. Anderzhanov and B. D. Khristoforov, Prikl. Mat. Tekh. Fiz., No. 5, 25-27 (1988).
3. V. V. Selivanov, V. S. Solov'yov, and N. I. Sysoev, Shock and Detonation Waves. Methods of Investigation [in Russian], Moscow (1990).
4. M. A. Tsikulin and E. G. Popov, Radiative Properties of Shock Waves in Gases [in Russian], Moscow (1977).
5. L. G. Gvozdeva and A. I. Kharitonov, in: Optical Methods of Investigation of Gas Flows and Plasma [in Russian], Minsk (1982), pp. 7-10.
6. V. A. Andrushchenko, M. V. Meshcheryakov, and L. A. Chudov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4, 141-147 (1989).
7. V. I. Artem'ev, V. I. Bergel'son, I. V. Nemchinov, et al., Mat. Modelirov., 1, No. 8, 1-11 (1989).
8. V. A. Andrushchenko and M. V. Meshcheryakov, Inzh.-Fiz. Zh., 62, No. 3, 465-472 (1992).
9. M. V. Meshcheryakov, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 6, 150-153 (1991).
10. V. A. Andrushchenko, Inzh.-Fiz. Zh., 57, No. 2, 270-274 (1989).
11. A. A. Gurin, P. S. Malyi, and S. K. Savenko, Shock Air Waves in Mining [in Russian], Moscow (1983).