TWO-DIMENSIONAL UNSTEADY FLOW IN A RADIAL CHANNEL

N. P. Gridnev, V. A. Derevyanko, and V. F. Kulikov

UDC 533.6.011

INTRODUCTION

In spite of a considerable development of numerical methods in recent years, the solution of gasdynamics problems related to shock-wave processes remains a complex problem. One such problem is the calculation of unsteady two-dimensional flows in T-shaped channels for the emergence of a shock wave from a flat or cylindrical pipe. The emergence from a narrow channel into a broad channel and the formation of a diffracted shock wave have been studied most. A number of theoretical [1-3] and experimental [4, 5] papers have been devoted to this problem. Less studied, particularly theoretically, is the problem of the reflection of a diffracted shock wave from an end wall and the subsequent development of flow in the channel. The difficulty is that appreciable gradients of the flow parameters appear in the region of reflected shock waves. This results from the instability of the difference scheme and leads to strong oscillations. In certain cases this phenomenon can be reduced by introducing smoothing terms into the difference scheme [6]. It is also known [7] that schemes of increased order of accuracy give appreciably smaller oscillations close to a discontinuity, and, in addition, the "smearing" zone of the discontinuity is minimal for these schemes. Preliminary calculations of the one-dimensional reflection of an incident shock wave from a solid wall showed that these schemes are stable for a large number of time steps (n = 800) and are highly accurate in the region of reflected shock waves [8].

Taking these facts into account, a scheme of the third order of accuracy analogous to that described in [9] was chosen for calculating unsteady flow in radial channels.

§1. The system of gasdynamics equations is written in the form

$$\partial \mathbf{f}/\partial t + \partial \mathbf{F}(\mathbf{f})/\partial z + \partial \mathbf{G}(\mathbf{f})/\partial r + \mathbf{H}(\mathbf{f}, r) = 0;$$

$$\mathbf{f} = \begin{vmatrix} \rho \\ \rho u \\ \rho v \\ l \end{vmatrix} \mathbf{F} = \begin{vmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (l + p) u \end{vmatrix} \mathbf{G} = \begin{vmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ (l + p) v \end{vmatrix} \mathbf{H} = 1/r \begin{vmatrix} \rho v \\ \rho uv \\ \rho v^2 \\ (l + p) v \end{vmatrix},$$

where $l = \rho u^2/2 + \rho v^2/2 + p/(\gamma - 1)$.

The density, velocity, pressure, and temperature scales are taken, respectively, as ρ, c, ρc^2, and T in the unperturbed gas ahead of the incident shock wave. In this case the gas parameters in the unperturbed flow have the values $\rho = 1$, $p = 1/\gamma$, and $T = 1$. The boundary condition at the solid walls is given by $v_n = 0$. The viscosity and thermal conductivity of the gas are neglected.

The calculations were performed on a BÉSM-6 computer using a program written in $\alpha-6$. The results were printed out in the form of isolines (isobars, isochors) and the velocity distribution. Numerical information was used to monitor the results. The parameters of the incident shock wave and the channel dimensions were taken from experiment.

The experiment was performed on a 55-mm-diameter shock tube which terminated in a radial channel 24 mm wide. The radial channel was located inside a vacuum chamber with two optical windows for Töpler photography.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 34-38, November-December, 1976. Original article submitted December 30, 1975.

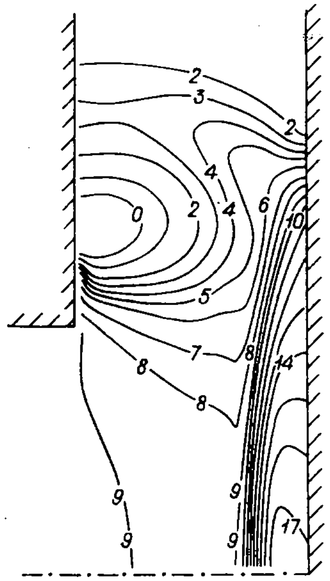

Fig. 1

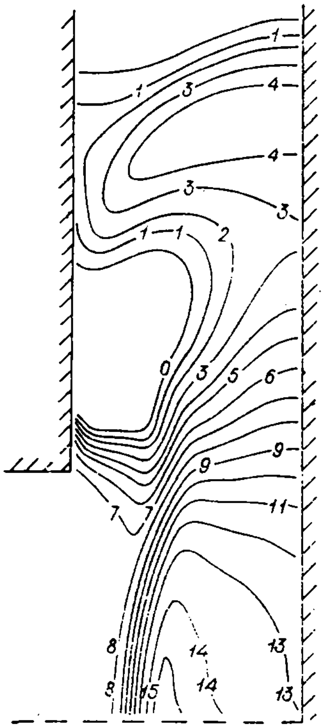

Fig. 2

The reflection of the diffracted shock wave and the subsequent flow in the radial channel were investigated by the Töpler method together with high-speed photography with a streak camera.

The schlieren apparatus was assembled from commercial objectives. The arrangement of the apparatus was conventional. For the joint operation of the instrument and the high-speed SFR-2M streak camera two objectives were placed after the knife edge as in [10]. The light source was an IFP-2000 lamp through which an artificial long line was discharged. The light beam traveled parallel to the walls of the radial channel and was converged in the plane of the knife, the edge of which was also parallel to the channel walls. The direct shadow image of the process in the radial channel was projected into the photographic film of the streak camera. The exposure time was 3 μsec per frame. In view of the symmetry of the process, half the channel was covered with an opaque screen. A shock wave with a Mach number M = 6.3 was produced in argon at an initial pressure of 25 mm Hg.

§2. The results of the calculations and the experiment are shown in Figs. 1-5. These graphs and photographs show the time development of the same process. Figures 1 and 2 show isochors at various times. Figure 1 shows the initial stage of the reflection of the diffracted shock wave from the end wall of the channel, and Fig. 2 shows the time when the reflected shock wave is converted into a standing shock wave, and the subsequent development of the process occurs mainly in the radial direction. In addition to the density distribution, Fig. 3 shows the isobars and Fig. 4 the velocity distribution corresponding to the same instant of time as in Fig. 2. Analysis of the velocity distribution (Fig. 4) shows that a stagnation zone arises behind the reflected shock wave in the region of the symmetry axis beyond which the flow turns in the radial direction. The velocity of the gas in this direction approaches the velocity of the gas behind the incident shock wave, and a shock wave is formed in the radial direction (Figs. 2 and 3) which merges with the diffracted shock wave.

A complex flow structure arises in the axial direction, since the reflected shock wave does not propagate in a homogeneous gas but interacts with the rarefaction wave which starts from the corner of the channel. This produces a curvature of the shock wave and an additional density gradient (contact discontinuity) behind it. The isochors here have a point of inflection. On the Töpler photographs (Fig. 5) this leads to the appearance of a λ-leg resting with its foot on the axis of symmetry. This phenomenon does not occur in the early stage of the reflection of the diffracted wave from the channel wall, as shown in the first frame of Fig. 5, since the interaction of the rarefaction wave with the reflected wave is still weak.

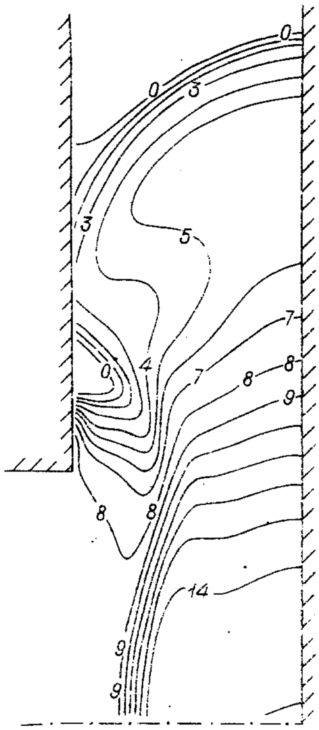

Fig. 3

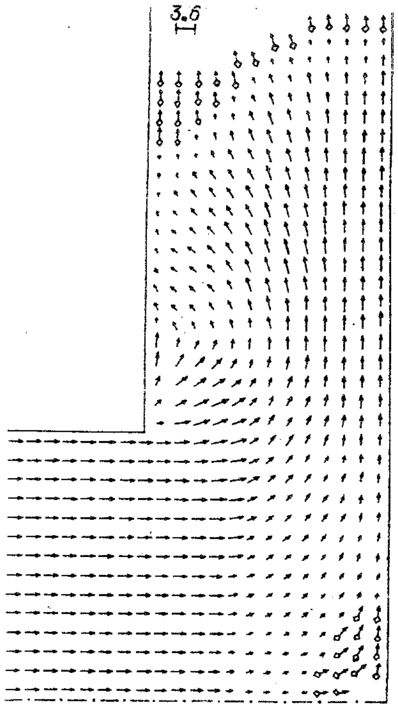

Fig. 4

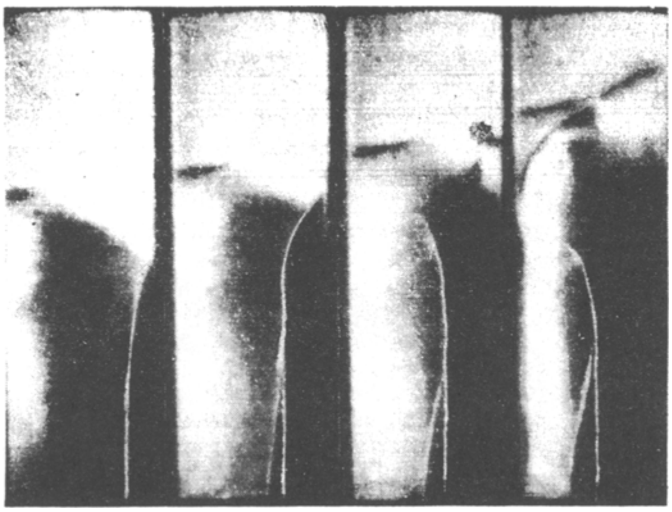

Fig. 5

TABLE 1

Fig. No.	Parameter \ Curve No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	ρ	0,64	0,84	1,1	1,4	1,6	1,8	2,1	2,7	3,2	3,7	4,2	4,8	5,3	5,8	6,4	6,9	7,4	8
2	ρ	1,1	1,4	1,6	1,9	2,2	2,5	3,0	3,4	3,8	4,2	4,7	5,1	5,5	5,9	6,3	6,6		
3	p	2	3,4	2,5	5,1	7,6	10	14	19	27	36	44	53	61	70	78	87		

From the experimental results shown in Fig. 5 the general pattern of development of the process can be traced rather clearly in spite of the inadequate resolving time and is in good agreement with the calculated results. This is true for both the space—time development and the shock-wave structure of the flow.

Since the flow process being studied is rather complex, an explanation of its characteristic properties requires plotting a large number of isolines in Figs. 1-3, each of which is numbered. The correspondence between the density, pressure, and number of the curve is given in Table 1.

The values of the pressure, density, and velocity of the gas behind the incident shock wave for $M = 6.3$ and $\gamma = 1.67$ are 29.5, 3.7, and 3.6, respectively, in dimensionless units. The velocity scale (3.6) is plotted in the upper part of Fig. 4. The velocity vectors whose origins are marked by diamonds are not drawn to scale, but show only the direction of flow; their values range from 0.3 to 0.5.

LITERATURE CITED

1. V. V. Rusanov, "Calculation of the interaction of unsteady shock waves with obstacles," Zh. Vychisl. Mat. Mat. Fiz., 1, No. 2 (1961).
2. G. M. Rudakova and A. P. Shashkin, "Calculation of certain two-dimensional unsteady flows of a gas," Izv. Sibirsk. Otd. Akad. Nauk SSSR, No. 1 (1975).
3. G. A. Tarnavskii, V. I. Khonichev, and V. I. Yakovlev, "Diffraction of a shock wave by a square corner and at exit from a two-dimensional channel," Izv. Sibirsk. Otd. Akad. Nauk SSSR, Ser. 8, No. 2 (1974).
4. B. W. Skews, "The shape of a diffracting shock wave," J. Fluid Mech., 29, 297 (1967).
5. T. V. Bazhenova, L. G. Gvozdeva, V. S. Komarov, and B. G. Sukhov, "Study of the diffraction of strong shock waves by convex corners," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4 (1973).
6. A. I. Ivandaev, "A method of introducing pseudoviscosity and its application to the refinement of difference solutions of the equations of hydrodynamics," Zh. Vychisl. Mat. Mat. Fiz., 15, No. 2 (1975).
7. V. V. Rusanov, "Difference schemes of the third order of accuracy for the through calculation of discontinuous solutions," Dokl. Akad. Nauk SSSR, 180, No. 6 (1968).
8. N. P. Gridnev and V. I. Yakovlev, "Investigation of difference schemes of increased order of accuracy for calculating reflected shock waves," in: Problems of Gasdynamics [in Russian], ITPM Sibirsk. Otd. Akad. Nauk SSSR, Novosibirsk (1975).
9. V. V. Eremin and Yu. M. Lipnitskii, "On the construction of multidimensional difference schemes of the third order of accuracy," Zh. Vychisl. Mat. Mat. Fiz., 14, No. 2 (1974).
10. A. S. Dubovik, "Photographic Recording of Rapidly Occurring Processes [in Russian], Nauka, Moscow (1975).