DECAY OF A SHOCK WAVE AT A PERFORATED BAFFLE

V. T. Grin', A. N. Kraiko, and L. G. Miller

UDC 533.6.011.72

The decay of a longitudinal discontinuity at a perforated baffle is considered, which occurs for example for normal incidence of a shock wave. With the passage of time, the linear dimensions representing the positions of the nonstationary inhomogeneities in the flow arising from the decomposition become much larger than the characteristic size of the perforations (the coordinates of the shock waves and of the contact discontinuity, and also the extent of the rarefaction waves). One is then justified in assuming a steady-state flow through the perforations (for the mean parameters in the presence of turbulent pulsations) and that the nonstationary flow as a whole is self-modeling. Under these conditions, the solution (in particular the reflection and transmission coefficients for the shock wave) may be determined on a model with assumptions on the steady-state flow of the gas through the baffle. Results on this topic include particularly the experimental data of [1-5] and the theoretical approaches developed in [4-8]. However, the latter do not give a complete solution. The topic is also related to experimental studies on nonstationary flow around obstacles in shock tubes [9] and to the decomposition of shock waves in channels with sudden changes in area. There is an extensive literature on this [10-18], which is partly used below.

1. We direct the x axis of a rectangular xyz coordinate system along the normal to the baffle, which resembles the initial discontinuity in coinciding with the plane x = 0. Then we consider the flow as a whole (global analysis), and neglect the thickness of the baffle and the characteristic linear dimension d of the perforations. Finally, without loss of generality, we assume that after the decomposition the gas flows through a perforation from left to right (in the positive direction of the x axis). For $d \ll |x| \ll Dt$, where t is time and D is the characteristic shock-wave speed, the flows to left and right of the baffle can be considered as uniform and stationary. We use subscripts minus and plus for the parameters of these flows, while subscript m is used for quantities averaged over the minimal cross sections of the holes. If p is pressure, ρ density, and i specific enthalpy (a known function of p and ρ), while u, v, and w are the x, y, and z components of the velocity vector **V**, $V = \sqrt{u^2 + v^2 + w^2}$ and $[\varphi] = \varphi_+ - \varphi_-$ for any parameter φ, then by virtue of the steady-state character of the flow through the baffle

$$[\rho u] = 0,\ [2i + V^2] = 0,\ [p + \rho u^2] = -X,$$
$$[\rho uv] = -Y,\ [\rho uw] = -Z. \tag{1.1}$$

Here X, Y, and Z are the corresponding projections of the force **F** acting from the flow on unit area of the baffle. System (1.1) should be supplemented with expressions for the components of **F** as functions of the parameters of the flow and baffle or by other information equivalent to these expressions. In particular, for a sufficiently thick baffle, in which the length of the channels is large by comparison with the transverse dimensions, one naturally assumes as follows no matter what the values of v_- and w_-:

$$v_m = v_+ = 0,\ w_m = w_+ = 0, \tag{1.2}$$

which replace the last two conditions in the previous system (in fact, these conditions can be used with (1.2) to determine Y and Z). Similarly, instead of specifying X it is often simpler and more convenient to assume some scheme for the flow of the gas through the baffle. This of course must be in conformity with the available theoretical and experimental evidence on such flows. For example, for subsonic flow to the left of the baffle one naturally assumes [2-8, 12, 13, 16, 17] that the gas expansion, which is accompanied by a fall in pressure, is isentropic, i.e.,

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 95-103, May-June, 1981. Original article submitted March 10, 1980.

0021-8944/81/2203-0372$07.50

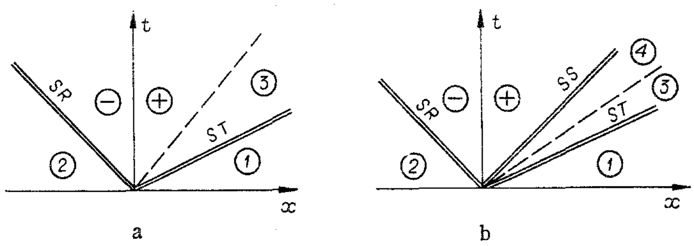

Fig. 1

$$s_m = s_-, \tag{1.3}$$

where s is the specific entropy or any function of this.

Let $\varepsilon = S_m/S$ be the degree of compression in the perforation, which is equal to the ratio of the minimal cross-sectional area S_m to the total area of the baffle S. As S_m it will be more correct to take not the geometrical area but the effective value, which incorporates the difference of the flow coefficient from unity. Then (1.2) and (1.3) along with the following relations consistent with (1.1):

$$\varepsilon\rho_m u_m = \rho_- u_-, \quad 2i_m + u_m^2 = 2i_- + V_-^2 \tag{1.4}$$

and the equations of state $i = i(p, \rho)$ and $s = s(p, \rho)$ constitute a system of conditions relating the parameters to the left of the baffle and in the minimal cross section.

We introduce the Mach number $M = u/a$, where $a = a(p, \rho)$ is the speed of sound. For $M_m < 1$ the flow to the right of the baffle will also be subsonic (here we are considering that flow near the baffle, i.e., for $|x| \ll Dt$; in a nonstationary wave structure, the gas speed can take any values to the left and right of the baffle). In this condition, which we call P1, it is unrealistic to assume expansion of the subsonic flow without detachment for x > 0. Here it is more correct to use the scheme for detached flow (Bord shock [11]), when there is a constant pressure $p' = p_m$ to the right of the baffle. At this stage we assume that the channels in the perforation either narrow in the flow direction or have constant cross sections. In P1, the third equation of (1.1) written for the sections m and + takes the form

$$p_+ + \rho_+ u_+^2 = p_m + \varepsilon\rho_m u_m^2. \tag{1.5}$$

Naturally, in this state the parameters appearing in (1.1)-(1.5) are found at the same time as the problem on the breakup is solved. We do not consider the order of the operations and the methods of analysis, which are completely analogous to those described in [12, 15, 17-19], and merely state that one then implements an xt diagram as shown in Fig. 1a. The double lines in Fig. 1 show the paths of the shock waves, while the broken lines represent the contact discontinuity (the trajectory of the baffle coincides with the t axis). Any of the shock waves can be replaced by a centered decompression wave.

The limit in relation to P1 is a flow that is sonic in the channel [2-5, 7, 8, 16]; then

$$M_m = 1, \tag{1.6}$$

and the flow for x < 0 ceases to depend on the parameters to the right of the baffle, but (1.1)-(1.4) still applies. In such states, the Bord shock does not occur, and the condition for realization is the inequality

$$p' \leqslant p_m. \tag{1.7}$$

When (1.6) and (1.7) are satisfied, there are at least two states of flow to the right of the baffle. In one of these (called P2), the value of p' is dependent on the nonstationary wave structure at x > 0, which in this case is the same as that shown in Fig. 1a. This means that the sonic jets emerging from the holes in the perforation by virtue of (1.7) initially accelerate, but in response to the stationary discontinuities (oblique and almost straight or closing [2]) together with the mixing form a uniform subsonic flow in the + section. We then have

$$\begin{gathered}\rho_+ u_+ = \varepsilon\rho_m u_m, \quad 2i_+ + u_+^2 = 2i_m + u_m^2,\\ p_+ + \rho_+ u_+^2 = \varepsilon(p + \rho u^2)_m + (1 - \varepsilon)p',\end{gathered} \tag{1.8}$$

and in the + section the solution providing a nondecreasing entropy has $M_+ < 1$. We must emphasize that although the parameters with subscript m in (1.8) are shown by (1.6) to be known in this state, (1.8) accords with the meaning of P2 in giving only a relationship between p', p_+, ρ_+, and u_+, without defining them unambiguously. These quantities are found by joint solution of (1.8) and the equations describing the wave structure of Fig. 1a for $x > 0$.

Along with P2, we examine P3, with shut-off shock-wave zones, where the flow at the baffle is independent of the wave structure to the right, in particular as regards p', p_+, ρ_+, and u_+.

Here the flow in the + section is supersonic, and the wave diagram is as shown in Fig. 1b, and the wave (shock or centered) separating the regions + and 4 moves in the opposite sense to the supersonic flow, although it is carried by it to the right. As in Fig. 1a, the shock waves (double lines) in Fig. 1b may be replaced by centered decompression waves in appropriate families.

To describe the P3 state with these zones we have to make additional assumptions. In some studies [4] the assumption has been made of isentropic supersonic expansion:

$$s_+ = s_m. \tag{1.9}$$

However, appreciable errors arise from using this equation to describe a stationary supersonic flow in a channel with sudden expansion, particularly in $p'/p_m = \varphi(\varepsilon)$, since this is well known from experiment for this state. In that sense a more perfect model is that obtained for zero ejection coefficient in the theory of [20] for ejector nozzles. This model corresponds to (1.8) with

$$p' = p_m \tag{1.10}$$

and with $M_+ > 1$; this relationship is a consequence of (1.8) and (1.10) with $M_m = 1$ and $M_+ > 1$ and gives $p'/p_m = \varphi(\varepsilon)$ that agrees exceptionally well with all the experimental data of which we are aware $(\varepsilon \geqslant 0.05)$ on sudden expansion of a sonic flow (see in particular [21]). As there are no such comparisons for $\varepsilon < 0.05$, the P3 state will subsequently be described within the framework of (1.10) and (1.9). In both cases the transition from P2 to P3 occurs when the secondary shock wave SS or the bundle of decompression waves from the characteristics of the second family, which separate zones + and 4 according to Fig. 1b, begin to be carried off by the flow to the right.

Let the shock wave SI be incident on the baffle at time $t = 0$, arriving from the left and being responsible for the discontinuity arising at that instant in the section $x = 0$. The intensity of SI may be characterized either by $P_I \equiv p_2/p_1$, or by the Mach number $M_{SI} \equiv D_{SI}/a_1$, where D_{SI} is the velocity of SI and the subscripts 1,... relate to the parameters in the corresponding regions; one then naturally expects successive realization of the P1, P2, and P3 states. On the basis of the conditions for transition from P1 to P2 and from P2 to P3 one can show that the dependence on P_I and M_{SI} of parameters such as the total pressure p' and the intensities of the transmitted wave ST and the reflected wave SR, i.e., $P_T \equiv p_3/p_1$ and $P_R \equiv p_-/p_2$, remain continuous. At the points of transition, there are only discontinuities in the slopes of the curves, which cannot always be seen on the scales of the figures. The proof of the continuity of these relationships on going from P2 to P3 is based, among other things, on the relations describing these states, together with either the conditions for a stationary step, which is a secondary SS wave at the instant of transition, or on the continuity of the parameters at the left boundary of the decompression wave.

Although the above sequence of states is quite natural, this does not mean that it will be realized under any conditions, in particular for all ε. For example, according to the above analysis the transition from P2 to P3 for very small ε is impossible for any P_I. For $\varkappa = 1.4$, the minimum value of ε indicated by (1.9) for which this transition can occur is close to 0.008, as against 0.023 on the basis of (1.10). For smaller ε and any large P_I one gets the P2 state with open zones in these models. Moreover, it can be shown that with the above scheme for flow to the left of the baffle and with any model for the flow to the right there must be some minimal value of ε that sets a lower bound to the permeability of the baffle for which the P3 state can occur. In other problems, as in the decomposition involving the sudden bursting of diaphragms in minimal cross sections of the perforation, one gets a sequence of all three states for any ε as the initial pressure ratio increases.

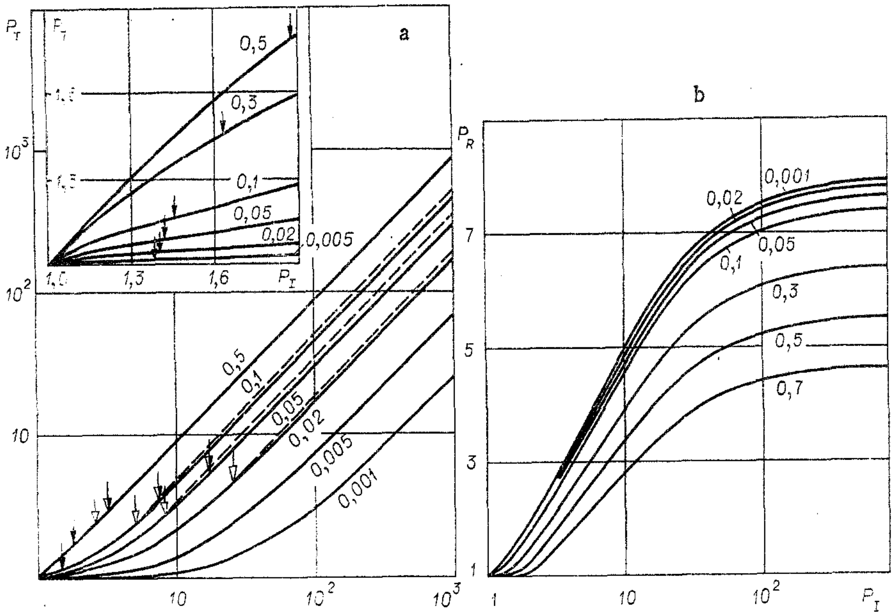

Fig. 2

2. Before we give numerical results obtained from the above model and compare them with the experimental evidence, we note some possible generalizations of the analysis.

Firstly, the analysis of section 1 is transferred comparatively easily to the case of perforations with expanding or contracting-expanding channels (in the flow direction). We do not give all the equations for this situation but merely enumerate the main points that must be considered in writing them. When weak shock waves do not occur, the modification of the P1 scheme amounts to the isentropic condition of (1.3) to emergence from the baffle on the assumption of undetached flow in the channels. Deviations from this scheme are to be expected only for channels with large angles of expansion, in which the retardation of the subsonic flow may result in detachment in the expanding parts.

When the shock waves occur, which occurs here in the minimal cross sections, we get the P2° state in a certain pressure range p' in the detachment zone, which is intermediate between P1 and P2. This range in p' is defined by the conditions

$$p(\mathrm{M_e})P(\mathrm{M_e},\ \mathrm{Re_e}) \leqslant p' \leqslant p(1), \tag{2.1}$$

where M_e and Re_e are the Mach and Reynolds numbers determined from the parameters at the exit from the channels, p(M) is the pressure found as a function of the Mach number, the total enthalpy $I_- \equiv i_- + V_-^2/2$ and s_-, and P(M, Re) is the critical pressure ratio in the oblique shock wave, which is known from experiment as a function of its arguments. The dependence of P on Re is weak for a turbulent boundary layer. If the left-hand inequality is violated in (2.1), i.e., we have

$$p' < p(\mathrm{M_e})P(\mathrm{M_e},\ \mathrm{Re_e}),$$

there is a transition to P2 and then to P3. Violation on the right inequality in (2.1) is equivalent to violating condition (1.6), i.e., transition to P1. If both inequalities are obeyed in (2.1), there are shock waves in the expanding part of each channel, and behind these (near the wall) there is a detachment zone, in which [22] $p \approx p'$, and the pressure in the detachment section p(M), the Mach number M, p', and so on are related by

$$p' = p(\mathrm{M})P(\mathrm{M},\ \mathrm{Re}) \geqslant p(\mathrm{M_e})P(\mathrm{M_e},\ \mathrm{Re_e}). \tag{2.2}$$

Subsequent calculation is performed as for P2, with the substitution of p_m, ρ_m, u_m, and ε in (1.8) of values that satisfy (2.2). The transition from P2° to P2 occurs continuously under violation of the left inequality in (2.1).

Secondly, the flow to the left of the baffle is considered subsonic ($M_- < 1$) for all the above states, whereas in reality the opposite situation is possible, particularly for $(1-\varepsilon) \ll 1$, , i.e., for a baffle that only slightly retards the flow. It is obvious, how-

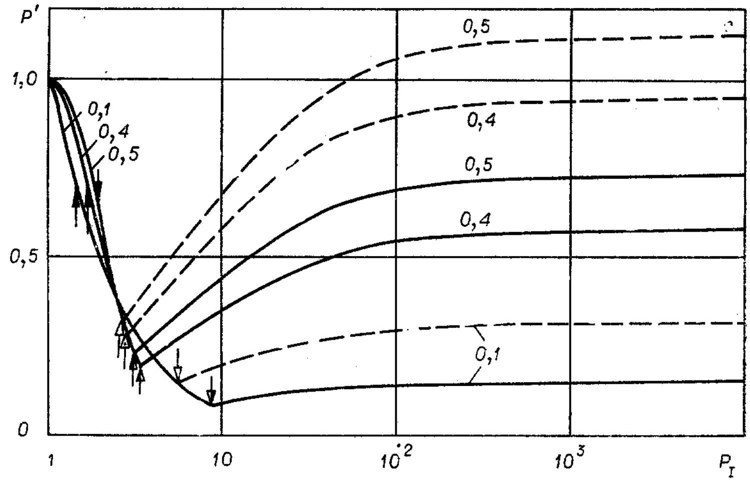

Fig. 3

ever, that the analysis of such states from one-dimensional flow models for the channels, if justified at all, is only for special baffles such as gratings consisting of elongated sharp-ended profiles. In the case of a baffle (screen) composed for example of wires, one more naturally uses all equations of (1.1) with

$$X = c_x(M_-, Re_-)(1-\varepsilon)\rho_- u_-^2 \qquad (2.3)$$

and with analogous expressions for Y and Z with nonzero values for v_- and w_- in the incident flow. To a first approximation, the resistance coefficients $c_x, \ldots$ can then be taken from theoretical and experimental studies on supersonic flow around single elements of the baffle (for circular cylinders for a wire screen). As ε falls, it becomes necessary to consider the interference between adjacent pairs of elements. The onset of interference (as ε falls) can be established from these results on flow around the individual elements. The interaction between the elements results in increased X, with accentuation of the stationary head shocks formed on flow around each element, and ultimately to failure of the supersonic flow state. It is more complicated to examine the transition state, where the interference is important but the flow between elements is far from one-dimensional. Here one can produce various paradoxes by using models analogous to those developed for $M_- < 1$. Here we would point out the possibility of several solutions, which in these conditions can occur for a channel with a sudden change of area and which vanish when one replaces the sudden change by a smooth one [13, 14]. For $(1-\varepsilon) \ll 1$ one is justified in using expressions of the type of (2.3) within the framework of (1.1) also for $M_- < 1$.

Finally, the above models can be readily incorporated into a scheme for nonstationary interaction of a shock wave of any orientation with a perforated baffle. It is particularly simple to describe the case of nonstationary interaction with regular reflections.

3. In accordance with the models of part 1, we wrote an algorithm for a computer and made calculations of the interaction of a shock wave with a perforated baffle. The channels were of constant cross section, while the gas was assumed perfect (with $\varkappa = 1.4$ if not otherwise stated). For that case, it is convenient to understand by s in (1.3) and (1.9) the entropy function $p/\rho^\varkappa$; Figs. 2 and 3 show some results, where here and subsequently the calculated values are shown as solid and broken lines, the second corresponding to the parts of the curves for which the P3 state is obtained within the framework of (1.9).

Figure 2a shows P_T as a function of P_I for various ε (numbers on the curves). The transition points are indicated by the arrows: P1 to P2 by filled arrows, P2 to P3 by open arrows for (1.9) and by half-filled ones for (1.10). The range in P_I from 1 to 10^4 is shown on a logarithmic scale. The initial parts of these curves are shown also on the usual scale in the upper part of the figure. Figures 2b and 3 show the reflected wave intensity P_R and the relative pressure $P' \equiv p'/p_2$ in semilogarithmic scales as functions of P_I and ε.

Figures 4 and 5 compare the calculations with the experimental data. In Fig. 4, the comparison is made with the results from [3, 4] for ε = 0.5, these sources being indicated respectively by open and filled points, while results for ε = 0.71 are compared with the ex-

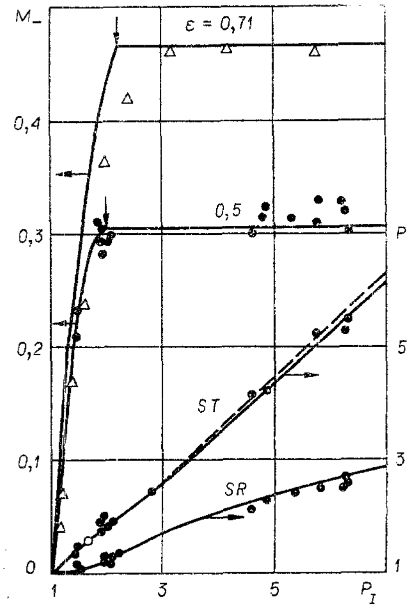

Fig. 4

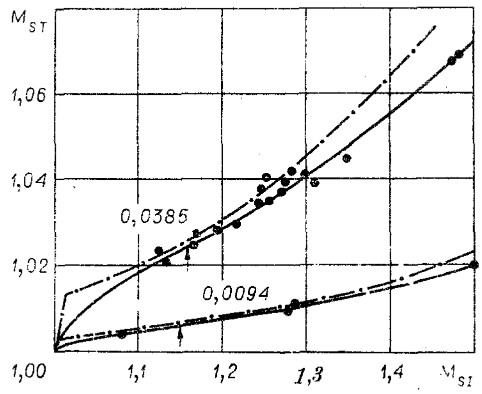

Fig. 5

perimental data from [2] (triangles). The results of [3] for the reflected wave are not given, since according to the arguments of [3], which are confirmed in [4], the measurements of [3] overestimated the reflected-wave intensity. In the comparison with [2], the flow coefficient was taken as 0.95, in accordance with the estimates of [2]. In other cases it was taken as one. The theoretical curves of [4] are not shown, although they are in good agreement with the experimental data from that source, for the following reasons. The theoretical description of P1 in [4] was based on experimental values for the resistance coefficients of perforated screens. The resulting curves hardly differ from the corresponding solid curves in Fig. 4, which should be considered as an additional confirmation of the scheme of section 1 for flow with Bord shock waves. In [4], a model was used for states with $M_m = 1$ with the isentropic condition of (1.9), which was written in section 1 for the P3 state. For $\varepsilon = 0.5$, this model can be used only above $P_I = 2.74$, when the second wave is carried away down the flow. Finally, for $M_m = 1$, the scheme of section 1 for the flow to the left of a perforated baffle does not differ from that used in [4].

In the same way, Fig. 5 compares the calculations for $\varkappa = 1.29$ and two small values of ε (numbers on the curves) with experimental data (points) and theoretical values (dot-dash lines) from [5]. Here M_{SI} and M_{ST} are the Mach numbers respectively of the incident and transmitted waves. The initial rectilinear parts of the dot-dash corresponding to the absence of shock in the channels were constructed in [5] on the assumption that (1.3) and (1.9) apply, i.e., within the framework of isentropic acceleration followed by retardation. In that case, in contrast to the model of section 1, the baffle has no resistance. Therefore, $P_T = P_I$ and $P_R = 1$, i.e., the incident wave SI passes through without attenuation and without reflection. Figure 4 shows that this is not so (in [5] there are no experimental points corresponding to this mode). We have been unable to establish what model was used in [5] for the shock-wave case. Nevertheless, it is clear that the dot-dash curves of Fig. 5 deviate from the solid lines, and the advantage of the latter becomes more obvious as M_{SI} or P_I increases. It is meaningless to compare theoretical curves with experiments of [9] on flow around fairly large obstacles for reasons concerned with the methods. The main one of these is that the distances at which the measurements of [9] were performed were small in relation to the dimensions of the bodies or the distances between them (the larger of these quantities acts as the characteristic dimension of the perforation d).

We are indebted to V. A. Vostretsova for assistance.

LITERATURE CITED

1. I. I. Glass and G. N. Patterson, "A theoretical and experimental study of shock-tube flows," J. Aerospace Sci., 22, No. 2 (1955).

2. D. S. Dosanjh, Some comments on 'A theoretical and experimental study of shock-tube flows,'" J. Aerospace Sci., 22, No. 11 (1955).
3. J. E. Bewman and G. B. F. Niblett, "The passage of a plane shock wave through a wire gauze," Proc. Phys. Soc., 68, part 12, No. 432 B (1955).
4. W. J. Franks and J. G. Hall, "Collision of plane shock waves with wire screens," J. Aerospace Sci., 24, No. 12 (1957).
5. C. G. Dain and J. P. Hodgson, "Generation of weak shock waves in a shock tube," Aeronaut. Quart., 25, part 2 (1974).
6. E. F. Zhigalko, "Simple solutions on the interaction of shock waves with permeable walls," in: Gas Dynamics and Heat Transfer [in Russian], Issue 4, Izd. LGU, Leningrad (1975).
7. G. L. Grodzovskii, "Interaction of nonstationary waves and perforated walls," Uchen. Zap. Tsentr. Aerogidrodinam. Inst., 6, No. 2 (1975).
8. E. N. Ostrovskii, "Absorption of the reflected shock wave from the interaction of a strong incident shock wave with a perforated obstacle," Uchen. Zap. Tsentr. Aerogidrodinam. Inst., 6, No. 5 (1975).
9. R. Kawamura and H. Kawada, "A study of the attenuation of shock waves due to obstacles in the passage," J. Phys. Soc. Jpn., 12, No. 11 (1957).
10. A. Kahane, W. R. Warren, et al., "A theoretical and experimental study of finite amplitude wave interactions with channels of varying area," J. Aerospace Sci., 21, No. 8 (1954).
11. K. P. Stanyukovich, Nonstationary Motions of a Continuous Medium [in Russian], GITTL, Moscow (1955).
12. V. G. Dulov, "Decay of an arbitrary discontinuity in gas parameters at a discontinuity in the cross-sectional area," Vestn. Leningr. Gos. Univ., Mat., Mekh., Astron., No. 19, Issue 4 (1958).
13. A. K. Oppenheim, P. A. Urtiew, and R. A. Stern, "Peculiarity of shock impingement of area convergence," Phys. Fluids, 2, No. 4 (1959).
14. G. Rudinger, "Passage of shock waves through ducts of variable cross section," Phys. Fluids, 3, No. 3 (1960).
15. A. K. Oppenheim, P. A. Urtiew, and A. J. Laderman, "Vector polar method for the evaluation of wave interaction processes," Arch. Budowy Maszyn, 11, No. 3 (1964).
16. W. Chester, "Propagation of shock waves in channels of variable cross section," in: Mechanics Problems [Russian translation], Issue 4, Izd. Inostr. Lit., Moscow (1963).
17. I. K. Yaushev, "Numerical calculation of nonstationary gas flows in the one-dimensional approximation for channels with discontinuities in area," Izv. Sibirsk. Otd. Akad. Nauk SSSR. Ser. Tekh. Nauk, No. 8, Issue 2 (1967).
18. I. K. Yaushev, "Decay of a longitudinal discontinuity in a channel with an area discontinuity," Izv. Sibirsk. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 8, Issue 2 (1967).
19. S. K. Godunov et al., Numerical Solution of Multidimensional Problems in Gas Dynamics [in Russian], Nauka, Moscow (1976).
20. H. Pearson, J. B. Holliday, and S. F. Smith, "A theory of cylindrical ejector supersonic propelling nozzles," J. Royal Aeronaut. Soc., 62, No. 574 (1958).
21. N. N. Slavyanov and R. K. Tagirov, "An experimental study of the effects of the specific heat ratio on the stagnation pressure behind a ring projection," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4 (1967).
22. H. L. G. Sinley and V. N. Ferriman, "Jet separation in conical nozzles," J. Royal Aeronaut. Soc., 68, No. 648 (1964).