ATTENUATION OF SHOCK WAVES BY SCREENS OF GRANULAR MATERIAL

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Experimental results on the attenuation of plane shock waves by screens of granulated material are outlined. A method is proposed for approximate calculation of the attenuating action of the screens.

The explosional safety of the processing and transportation of fuel gases and flammable liquids is ensured in many cases by means of fire retardants [1], often in the form of screens of granulated materials. In an emergency, pressure waves and shock waves (SW) may form in the channel fitted with the fire retardant. In [2, 3], the propagation of plane SW in filled and porous media was investigated. The fast quenching of the waves observed permits the hypothesis that such media may serve as effective means of SW quenching in channels. The present work outlines an approximate method of calculation and a detailed experimental investigation of the attenuation of plane SW by screens of granulated material.

To determine the attenuating action of the screens, in the general case, the complete flow pattern inside the porous sample must be considered. Model experiments [2] indicate that an ordered wave structure arises behind a plane SW entering a uniformly obstructed volume, and the leading front has weakly expressed discontinuities. The system of reflected density discontinuities generating inhomogeneity in the thermodynamic parameters and the velocity over the channel cross section is considerably attenuated behind the leading front at distances of the order of a few particle diameters. These features permit the assumption that a one-dimensional (hydraulic) approach is applicable for the description of the dynamics of SW quenching in the given systems.

The interaction of the flux with the packing particles leads to loss of gas momentum and redistribution of energy because of the formation of secondary discontinuities and turbulization of the flow. The drag coefficient of the particles in the packing may be written as the sum $c_f = c_{fp} + c_{fd}$. As a rule, the surface-friction forces are small in comparison with the surface pressure (of the form) and may be neglected, i.e., $c_{fd} \ll c_{fp}$ [4]. In these conditions, when the Reynolds analogy does not hold, heat transfer with the channel walls and the particles is small and may be neglected in the overall energy balance [3, 4]. To calculate c_f in a motionless layer of particles in conditions of steady flow, the Ergan equation is used, for example [4]:

$$c_f \approx c_{fp} = \frac{75}{\mathrm{Re}} + 0.875, \tag{1}$$

where $\mathrm{Re} = \varepsilon\rho du/(1 - \varepsilon)\mu$ when $0.4 < \varepsilon < 0.65$. It follows from Eq. (1) that c_f tends to the constant value 0.875 when $\mathrm{Re} \gtrsim 10^4$, i.e., the medium conforms to a quadratic drag law. In SW propagating in filled porous media, such values of Re are attained with an excess pressure of more than 5 kPa at the front (with $d \sim 1$ mm). In connection with this, it is assumed below that, with nonsteady gas flow behind the SW, the drag coefficient is determined by Eq. (1) as $\mathrm{Re} \to \infty$, i.e., depends solely on the characteristics of the filled medium. In addition, it is assumed that the local Mach number of the flow also has little influence on the drag coefficient. Thus, the problem of determining the attenuation of SW by a screen of granulated material may be reduced to the consideration of one-dimensional flow of impact-compressed gas with momentum losses specified by a quadratic drag law.

Consider the evolution of an SW of step profile after entering filled medium in the tube section $0 \le x \le h$ (h is the screen length). Suppose that the SW moves initially at

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TABLE 1. Experimental Screens

Material	Form of particles	d, mm	ε	h, mm
Polyethylene	Round	3,9	0,38	10, 25, 60
Steel	Cylindrical	10×12	0,41	35, 110, 160
Porcelain	Spherical	15,8	0,44	35, 60, 110, 160
Clay filler	Round	21,9	0,50	60, 160, 250

constant velocity in the section $-\infty < x < 0$ with a free cross section and with a hydraulically smooth surface. With the given assumptions, the basic equations of perfect-gas flow in the tube take the form

$$\rho_t + u\rho_x + \rho u_x = 0,\ \rho u_t + \rho u u_x + p_x = -F,$$
$$p_t + up_x - a^2(\rho_t + u\rho_x) = (\gamma - 1)Fu,\ p = \rho RT. \tag{2}$$

Here the subscripts t and x denote differentiation with respect to time and the coordinate. On the sections $-\infty < x < 0$ and $h < x < \infty$, the pressure loss $F = 0$; in the screen $F = 1.75\rho u|u|(1 - \varepsilon)/\varepsilon d$, where it is taken into account that $c_f = 0.875$. The initial conditions on SW input into the screen are

$$t = 0,\ -\infty < x \leqslant 0,\ M = M_0,\ \rho = \rho_0 \frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2},$$
$$u = \frac{2a_0}{\gamma + 1}\left(M - \frac{1}{M}\right),\ p = p_0\left[\frac{2\gamma}{\gamma + 1}M^2 - \frac{\gamma - 1}{\gamma + 1}\right]; \tag{3}$$
$$t = 0,\ 0 < x < \infty,\ \rho = \rho_0,\ u = 0,\ p = p_0. \tag{4}$$

Here M_0 is the initial Mach number; subscript 0 denotes the unperturbed medium. At an arbitrary time, Eq. (3) holds when $x \to -\infty$ and Eq. (4) when $x \to \infty$.

Despite the numerous simplifications, an accurate solution of Eq. (2) cannot be obtained. Most problems of nonlinear SW interaction with bounding surfaces and bodies are only susceptible to approximate solution. In connection with this, the approach developed in [5] is very successful. Following [5], it is assumed that the perturbed state behind the SW front has no influence on its motion, i.e., all the change in SW velocity is due to interaction of the front with the obstacle. The method of [5] is to substitute Eq. (3) into the equation for the C_+ characteristic obtained from Eq. (2). The solution of the final differential equation takes the form

$$G(m_0) - G(m) = 1.75\frac{1 - \varepsilon}{\varepsilon d}x. \tag{5}$$

In the linear approximation, $m = M - 1$, $m_0 = M_0 - 1$, and $G(m) = -(\gamma + 1)/2m$. Linear analysis of Eq. (2) in [3] leads to an analogous relation. For the case of arbitrary initial SW intensity, $m = M$, $m_0 = M_0$, and

$$G(m) \approx 4\frac{0.4m - 1}{m^2 - 1} + 4\ln(m^2 - 1) + 0.8\ln\frac{m + 1}{m - 1}. \tag{6}$$

Equation (6) is an approximation of the accurate function G(m) when $\gamma = 1.4$, giving a deviation of less than 3% in the range $1.01 < m < 4$.

To determine the region of applicability of the approximate solution in Eq. (5), numerical integration of Eq. (2) is undertaken by the method of shock-smearing calculation with the introduction of an artificial viscosity. Calculation shows that Eqs. (5) and (6) give satisfactory results, at least for $M_0 \leq 2$. This permits the assumption that Eqs. (5) and (6) are applicable for the approximate calculation of the excess pressure at an SW front of initially step profile undergoing attenuation in a screen of granulated material. Thus, it follows from the analysis that the SW intensity at the output from the screen (i.e., when

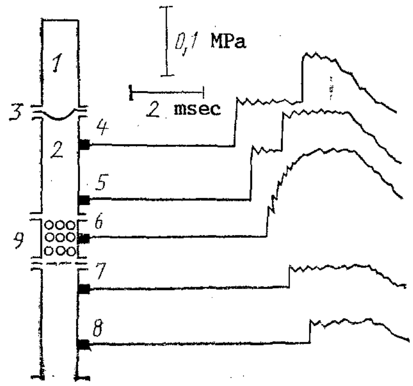

Fig. 1

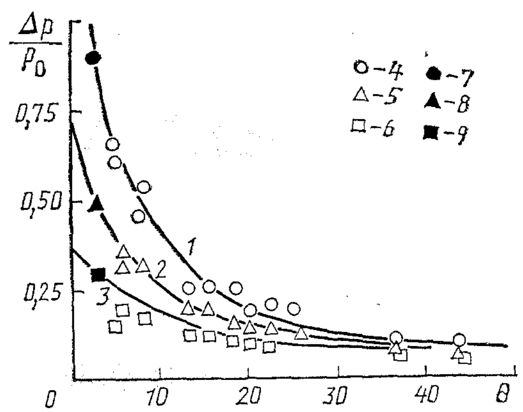

Fig. 2

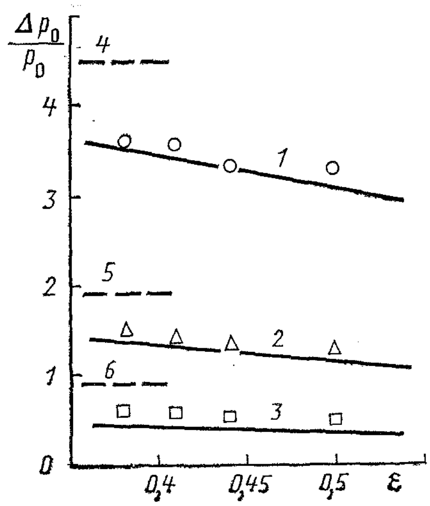

Fig. 3

Fig. 1. Diagram of experimental apparatus and typical pressure profiles.

Fig. 2. Amplitude of transmitted SW; 1-3) calculation; 4-6) experiment (filled screen); 7-9) experiment (perforated partition); M_0 = 1.47 (1, 4, 7), 1.28 (2, 5, 8), and 1.15 (3, 6, 9).

Fig. 3. Amplitude of reflected SW as a function of the porosity (permeability): curves 1-3) experiment [6] (perforated partition); points) experiments (filled screen); 4-6) pressure after reflection from rigid impermeable wall; M_0 = 1.47 (1, 4), 1.28 (2, 5), and 1.15 (3, 6).

x = h) is determined by M_0 and dimensionless complex $\theta = 1.75(1 - \varepsilon)h/\varepsilon d$ characterisizing the properties of the screen.

To verify the proposed relations, systematic experiments are undertaken on the SW attenuation by screens of various granulated materials (Table 1) with parameters close to those used in practice [1]. The experiments are conducted on a vertical shock tube with a channel of cross section 40 × 40 mm. The apparatus is shown schematically in Fig. 1. The high-pressure chamber 1 (length 0.5 m) is separated from the low-pressure chamber (LPC) 2 (length 2 m) by dividing membrane 3. Nitrogen is used as the propelling gas; air at a pressure p_0 = 0.1 MPa is used in the LPC. Behind dividing membrane 3, a shock wave is formed in LPC; its parameters are recorded by piezoelectric pressure sensors 4-8 and S8-17 and S8-13 oscillographs. In the LPC, at a distance of 0.9 m from the membrane, an insert 9 filled with granulated material is mounted. In the lower part of insert 9, a perforated partition is fitted, to retain the filled medium in the SW process. As well as the partition, grids with a cell dimension of 2 mm are fitted at the lower and upper ends of the screen. The grids and the perforated partition have no pronounced influence on the flow, since their total thickness (3 mm) is considerably less than the length of the screens employed, and the permeability exceeds ε. This construction of the screen is analogous to that in industrial fire retardants with granulated materials [1]. The parameters of the SW incident at the screen are determined using sensors 4 and 5 and those of the transmitted SW by sensors 7 and 8. The distance from sensor 5 to the upper boundary of the filled medium and from sensor 7 to the lower boundary is 13 cm. There is a 20-cm gap between sensors 4, 5 and 7, 8. In individual experiments, sensor 6 is mounted in the middle of the screen, so as to record the flow pattern there. The Mach number of the incident SW is varied in the range M_0 = 1.1-1.5. Sensors 4, 5 also record the parameters of the SW reflected from the boundary between the gas and the filled medium.

On the right-hand side of Fig. 1, the pressure profiles obtained experimentally with a screen (length 60 mm) of porcelain spheres (M_0 = 1.28) are shown. It is evident that the incident SW of step profile is transformed, after entering the filled medium, to a wave of lower intensity with smooth increase in pressure behind the front. This effect was also observed in [2]. After leaving the screen, the SW is of considerably lower intensity than the incident SW and is characterized by a clearly expressed step pressure profile. Note that, when $\theta \gtrsim 20$, a small (20-30%) increase in pressure behind the leading front is seen in the transmitted SW.

In Fig. 2, the values of $\Delta p/p_0$ calculated from Eqs. (5) and (6) are compared with experimental data, as a function of M_0 and the screen parameters; here Δp is the excess pressure at the front of the transmitted SW. Satisfactory agreement of the results is seen. It follows from Fig. 2 that, when $\theta \gtrsim 30$, the amplitude of the transmitted SW is practically independent of the initial intensity of the waves in the given range of M_0. Hence, for quenching of such SW, the parameters of the flame retardant, in practice, must satisfy the condition $\theta > 30$.

Some remarks may be made regarding the range of applicability of Eqs. (5) and (6) for the calculation of SW attenuation by screens of granulated material. As $h/d \to 1$, the parameter θ and hence the amplitude of the transmitted wave depend basically on M_0 and ε. Note, however, that the relation used for the pressure loss is valid when $h/d \gg 1$. Nevertheless, an analogous result is observed in investigating SW quenching by perforated partitions [6, 7]: the SW attenuation is specified only by the permeability of the partition and the Mach number of the incident wave. Points 7-9 in Fig. 2 show experimental data [6, 7] for a perforated partition with a permeability of 0.4. Comparison with the experimental data for screens of granulated material (ε = 0.38-0.5) shows that, in the limiting case as $h/d \to 1$, the filled layer is modeled by a perforated partition with a permeability of ε (neglecting the possible change in ε as $h/d \to 1$ in comparison with $h/d \gg 1$). In connection with this, it is expedient to compare the action of a perforated partition and a granulated medium on SW with respect to any other parameter. The excess pressure of the SW reflected from the surface of the filled medium Δp_0 is chosen as such a parameter here; it is measured in the experiments.

The dependence of $\Delta p_0/p_0$ on ε is shown in Fig. 3 for screens of minimal length (h/d = 2.2-3.2), together with the results of [6] for the SW reflected from a perforated partition, where ε corresponds to the permeability of the partition. It is evident that the agreement between the data for the filled screens and perforated partitions is good. That the pressure values of the reflected SW for the filled screens are somewhat too high is associated with the absence of through passageways even in layers with h/d = 2-3. Note that the pressure of the SW reflected from the filled screen is of practical interest, since this is what basically determines the choice of strength characteristics of the screen. As in the case of perforated partitions, Δp_0 is lower than the pressure of the SW reflected from a rigid impermeable wall; it decreases with increase in ε and increases weakly with increase in length of the screen.

Thus, the attenuation of plane SW by screens of granulated material has been systematically investigated. It has been shown that such screens are effective means of quenching SW. A method has been proposed for approximate calculation of the attenuating action of the screens. It has been established that, with a small length of the screen, its action on the SW is the same as that of a perforated partition with equivalent permeability.

NOTATION

c_{fp}, c_{fd}, drag coefficients of pressure (form) and friction; Re, Reynolds number; ε, d, porosity and mean particle diameter of filling; x, coordinate; t, time; ρ, u, μ, p, a, [illegible], γ, density, velocity, dynamic viscosity, pressure, sound velocity, temperature, and specific-heat ratio of gas; M, Mach number of shock wave; R, gas constant.

LITERATURE CITED

1. I. I. Strizhevskii and V. F. Zakaznov, Industrial Fire Retardants [in Russian], Moscow (1966).
2. B. Rogg, D. Hermann, and G. Adomeit, Int. J. Heat Mass Trans., 28, No. 12, 2285-2298 (1985).
3. N. Zloch, Arch. Mech., 28, No. 5-6, 817-825 (1976).
4. G. Wallace, One-Dimensional Two-Phase Flows [Russian translation], Moscow (1972).
5. J. Whitham, Linear and Nonlinear Waves [Russian translation], Moscow (1977).
6. V. D. Shevtsov, Interaction of Shock Waves with Permeable Obstacles. Paper No. 1192 Deposited at VINITI [in Russian], Moscow (1982).
7. B. E. Gel'fand, S. P. Medvedev, A. N. Polenov, and S. A. Tsyganov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 174-176 (1987).

RESONANT EXCITATION OF SPIRAL VORTEX STRUCTURES

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The effect of resonant amplification of the amplitude of spiral vortex structures on the surface of a differentially rotating shallow liquid is detected experimentally.

The importance of nonlinear perturbations in a rotating fluid in heat and mass transport processes has stimulated the study of the dynamics and wave properties of different space-time structures [1, 2]. The problem is often studied experimentally using shallow rotating liquids [3-5]. Spiral surface waves were studied experimentally in [6] using a container with a differentially rotating parabolic bottom. The spiral surface waves were generated in the region of velocity shear and they rotate with an angular velocity not equal to the velocity of rotation of the system as a whole. The possibility of controlling the amplitude of the spiral arms of the surface waves by means of forcing the rotating liquid to flow against a ring of obstacles was predicted theoretically in [7]. The resonant amplification of the amplitude of spiral waves on the surface of a rotating liquid has not been observed experimentally up to now.

The experimental apparatus is a cylindrical container of height 0.25 m with a flat bottom. The sides of the container are made of a material transparent to visible light. The bottom of the container is composed of a disk of radius 0.1 m and two rings of widths 0.1 and 0.3 m. The disk and rings rotate independently of one another with different angular velocities and in different directions [8]. The depth of the liquid (water) used in the experiments was 0.035 m. Motion of the surface of the water was visualized by nonwettable foam plastic particles with diameter of order 500 μm and was recorded by a camera mounted so that it remains at rest. At the shear boundary, i.e., at the distance R_k = 0.1 m, a ring of obstacles was placed. Each obstacle is a hemisphere of diameter 0.04 m and height 0.01 m. The obstacles were mounted on the central disk and the distance between obstacles was constant. The number N of obstacles was varied from one to four. A pressure tensotransducer was used to measure the amplitude of the disturbance [9]. The change of the amplitude of the pressure oscillations at a given radius in the form of an electrical signal was recorded by a digital voltmeter and then fed into a microcomputer for analysis.

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