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MEASUREMENT OF THE VELOCITY OF WEAK DISTURBANCES OF BULK DENSITY IN POROUS MEDIA

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Fire stops with fillings consisting of granulated materials are widely used in the chemical, gas, and petroleum industries [1]. Present semiempirical estimates make it possible in each given case to select the fillings necessary to protect against explosion during production. However, such estimates do not reveal the mechanism of interaction of combustion waves and, especially, detonation waves with bulk systems within a broad range of materials and sizes of the granules. Nevertheless, it was shown in [2-4] that the combustion and detonation of gases in inert porous media are quite different from combustion and detonation in the absence of a solid phase. This is manifest, for example, in anomalous combustion and detonation velocities.

To determine the mechanism responsible for these phenomena, it is important to consider the gasdynamic characteristics of bulk and porous systems, particularly the speed of sound. However, it must be noted that one feature of flows of two-phase gas–particle media is the presence of friction and heat exchange between the phases. This precludes the existence of nonsteady isentropic motions in such systems.

It is known [5] that the state of a gas in viscous flow can be described by the polytropy equation

$$p\rho^{-n} = \text{const},$$

where p and ρ are the pressure and density of the gas; n is the polytropy index. From here we introduce the notion of a characteristic velocity of the given process [5]:

$$u^2 = np\rho^{-1}. \tag{1}$$

When $n = \gamma$ (γ is the ratio of the specific heats of the gas), i.e., in the case of isentropic flow, the characteristic velocity will be the speed of sound.

A large number of studies has been devoted to the question of the speed of sound (i.e., the rate of propagation of small pressure perturbations with constant entropy) in a gas–particle medium. These studies can be divided into two groups. The first group contains studies of systems with a slow volume concentration of solid (or liquid) particles. In this case, a gas suspension is equivalent to a gas with the speed of sound [6]

$$a_e^2 = a^2\Gamma\left[\gamma(1+\eta)(1-\beta)^2\right]^{-1}, \tag{2}$$

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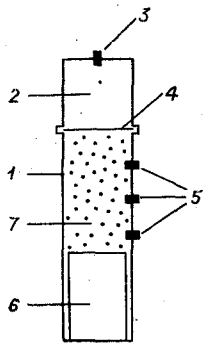

Fig. 1

where a_e is the equilibrium speed of sound in the gas suspension; a is the speed of sound in a pure gas; Γ is the ratio of the specific heats of the dust-bearing gas; η is the ratio of the mass of the particles to the mass of the gas; β is the volume fraction of particles in the gas suspension. As was shown in [6], the applicability of the model in [6] to bulk systems is limited.

A theoretical examination was made in [7] of the propagation of weak perturbations in moderately concentrated gas suspensions with allowance dynamic and thermal relaxation of the particles. However, the relations presented for relaxation time are valid only at particle volume concentrations $\beta < 0.2$-0.3. The assumptions made in [7] preclude the use of the results in [7] for bulk systems with $\beta = 0.65$-0.75.

The second group of studies has focused on compression waves in soils and rocks. The medium is described by continuum laws of the mechanics of deformable solids [8]. However, here the speed of sound in a continuous material is used, as is consistent with the goals of these studies. The nonsteady flow of a mixture of a gas and soil particles with a large volume content of the latter was examined in [9]. However, the velocity of small perturbations as a characteristic of the bulk medium was not discussed.

Thus, it is interesting to consider the problem of determining the gasdynamic properties of bulk systems as a whole. Here, we measured the velocity of a weak perturbation in the form of an unloading wave in a broad range of materials and sizes of particles of the bulk medium. We also considered gas pressure in the pores.

Tests were conducted on a vertical shock tube 1.5 m long with an inside diameter of 50 mm (Fig. 1). The high-pressure chamber (HPC) 1 was equipped with three piezoelectric pressure transducers 5. The distance from the membrane 4 to the first transducer was 21 cm, while the transducers were separated by a distance of 24 cm. The perturbing gas was nitrogen or helium in the HPC and air in the low-pressure chamber (LPC) 2. An insert 6 was used to shorten the working part of the tube. The number 3 denotes the triggering element. The bulk medium 7 was placed in the HPC. After the membrane ruptured (at a gas pressure p_0 in the HPC), a rarefaction wave propagated in the HPC. The velocity of the front of this wave was measured with the transducers and recorded by S8-13 oscillographs over distances of 24 and 48 cm.

The weak perturbation was modeled by a specially chosen unloading pulse. The pulse was generated with the aid of an HPC 1 cm long. Figure 2 shows typical oscillograms of the unloading pulse in the gas (the top oscillogram: $p_0 = 0.9$ MPa, 500 μsec on the horizontal scale, 0.07 MPa on the vertical scale) and in the bulk medium (bottom oscillogram: $p_0 = 1.9$ MPa, 1000 μsec on the horizontal scale, 0.03 MPa on the vertical scale). It is evident that in the tests $\Delta p/p_0 < 0.1$ (Δp is the maximum pressure drop in the unloading pulse). Satisfaction of this inequality was taken as the criterion of smallness of the given perturbation.

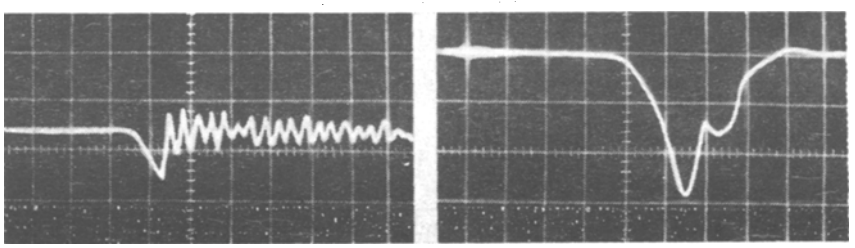
Fig. 2

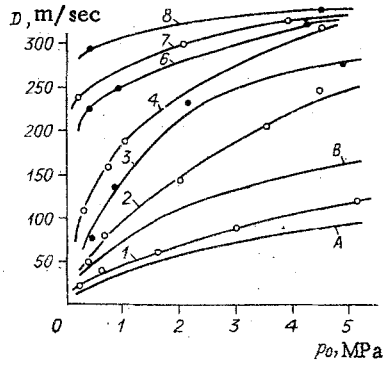

Fig. 3

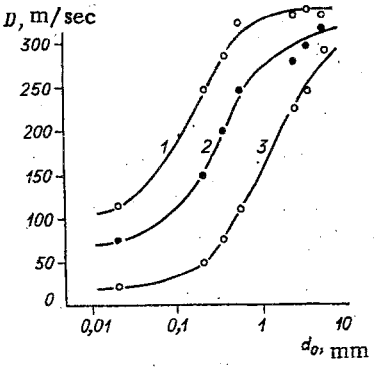

Fig. 4

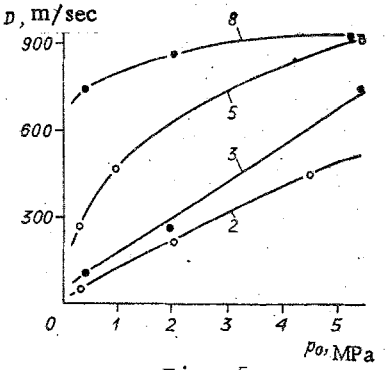

Fig. 5

To prove the reliability of the method, in adjustment tests we measured the speed of sound in an HPC filled with nitrogen or helium (98% helium + 2% air) from the velocity of the rarefaction wave over 24 and 48 cm; we obtained complete agreement between the measured and known values — 340 and 950 m/sec.

The velocity of the unloading pulse chosen for study does not depend on the height of the column of the bulk medium and is determined only by the properties of the medium. Thus, it can be taken as a characteristic of the given system.

In the tests, we varied the dispersion and material of the particles of the bulk material (see Table 1). Standardized screens were used to disperse the material. The mean particle size d_0 was determined with a tool microscope. The bulk density ρ_n and volume concentration β of the solid phase were determined independently. It can be seen that all of the materials studied can be divided into two groups: materials 1, 2, 4, 5, and 7, with a mean density ρ_p = 2.5 g/cm^3; materials 3, 6, 8, with ρ_p = 0.65 g/cm^3. Each material in each group differs only in the sizes of the particles (the volume fraction of the solid phase $\beta \approx 0.7$ for all of the materials except 1).

The results of the tests are shown in Figs. 3 and 4 (nitrogen in the HPC; the numbers on the curves on Fig. 3 correspond to the numbers in the table — for example, 1 is the powder, etc.). The measurement error for the velocity of the rarefaction wave is less than 20% at $p_0 < 2$ MPa and less than 10% at $p_0 \geq 2$ MPa. Figure 3 shows the experimental dependence of the velocity D of the front of the unloading pulse on pressure p_0 in the system. It can be seen that an increase in particle (pore) size is accompanied by a weakening of the dependence on pressure and an increase in velocity. Curve A was constructed for materials 1, 2, 4, and 7 from Eq. (2), while curve B was constructed for materials 3, 6, and 8. Figure 4 shows the dependence of the velocity D on particle size with fixed pressures p_0 = 0.3, 2.0, and 5.0 MPa (lines 3-1). It is apparent that the velocity of the unloading pulse in systems 1, 2, 4, and 7 on the one hand and 3, 6, and 8 on the other hand — these two groups containing materials with markedly dissimilar properties — changes in relation to particle (pore) size in the same manner. The results obtained for both groups of materials lie on one curve within the limits of the experimental error. This remains true with a change in pressure.

Thus, the velocity of small perturbations in bulk systems is independent of the material of the particles and depends only on the size of the particles (or the size of the pores between them) and the gas pressure in the gaps between particles.

TABLE 1

No.	Material studied	ρ_p g/cm^3	ρ_n g/cm^3	β	d_0, mm
1	Powder	2,70	0,81	0,30	0,02
2	Sand 1	2,45	1,78	0,73	0,20
3	Polystyrene	0,60	0,43	0,70	0,35
4	Sand 2	2,42	1,66	0,69	0,50
5	Sand 3	2,40	1,72	0,72	0,90
6	Porous polyethylene	0,50	0,31	0,62	2,40
7	Sand 4	2,34	1,70	0,73	3,0
8	Granules of polyethylene	0,82	0,55	0,67	4,5

The formal approach in [5] makes it possible to correlate each value of measured velocity D with a certain value of the polytropy index n. Then from Eq. (1) we have

$$u = D = (np\rho^{-1})^{0,5};$$

where $n = n(p_0, d_0)$ is a function of the initial pressure in the system and particle (pore) size.

It can be shown from analysis of gasdynamic equations on the front of the unloading wave that in a polytropic process the change in pressure over time at a fixed point depends on the polytropy index n. At $n \geqslant 1$, we have the classical profile of a rarefaction wave in a gas (see Fig. 2, gas) with a well-defined removable pressure discontinuity on the wave front. Such oscillograms were seen in the bulk medium at $D > 290$ m/sec (corresponding to $n \geqslant 1$). At $0 < n < 1$, the profile of the rarefaction wave is transformed and the removable discontinuity is absent. This was observed at $D < 290$ m/sec (see Fig. 2, bulk medium).

It is clear from comparison with the "equilibrium" speed of sound (see Fig. 4) that at $d_0 < 20$ μm ($p_0 = 0.1$-5.0 MPa), Eq. (2) can be used to evaluate the velocity of small pressure perturbations in bulk systems (with an error of 20%). At $d_0 > 2$ mm, the speed lies within the range D = 250-330 m/sec, i.e., is close to the "frozen" speed of sound. For estimates, it can be taken equal to the speed of sound in the gas (nitrogen). The "transitional" range in which it is necessary to specifically consider particle (pore) size lies in the range $d_0 = 0.02$-2 mm.

Figure 5 shows the dependence of the velocity of the front of the rarefaction wave D on the initial pressure p_0 in the bulk system in the presence of helium in the HPC (a mixture of 98% helium + 2% air, a = 950 m/sec). It is evident that replacement of the gas has no effect on the general character of the relations (see Fig. 3).

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