

ATTENUATION OF DETONATION WAVES IN LAYERS OF
HOMOGENEOUS AND INHOMOGENEOUS MONODISPERSE
GAS SUSPENSION IN SHARPLY EXPANDING PIPES

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Abstract: Mathematical simulation of the propagation mechanisms of combustion waves and heterogeneous detonation in sharply expanding pipes was performed using the equations of two-dimensional axisymmetric unsteady motion of a reacting mixture of a gas and monofuel particles. The interaction of a passing detonation wave in gas suspensions of a unitary fuel with an obstacle is studied. It is established that a decrease in the diameter of the particles of the unitary fuel leads to a decrease in the maximum pressure on the wall. It is shown that, under other identical conditions, the distribution of the concentration of particles of unitary fuel according to a linearly decreasing law leads to the greatest decrease in the maximum pressure on the barrier than according to a linearly increasing and homogeneous one.

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1. Introduction

For a number of branches of modern technology and technologies related to the use of explosive processes, the problem of attenuation of shock and detonation

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waves in gases is of great practical interest. In particular, the interest in this problem is due to the point of view of labor safety during blasting, protection of technological equipment, etc. One of the possible technical solutions to the problem of suppressing explosive waves in gases is the use of shielding layers of gas suspension.

In [1], the influence of reaction parameters (in particular, activation energy) on flows during diffraction of a plane detonation wave behind a ledge was studied by numerical modeling methods. The existence of three propagation modes has been confirmed, which are designated as subcritical (detonation failure), critical (partial failure with recovery) and supercritical (continuous propagation). The transition from one mode to another is associated with a change in the activation energy (which also causes a change in the length of the reaction zone). The possibility of the occurrence of a system of transverse waves behind the detonation front in one of the modes is indicated. In [10], the results of numerical analysis of the flow structure in comparison with experimental Schlieren photographs during the propagation of cellular detonation in a channel with a section break are presented. The influence of the size of the wide part of the channel on the propagation modes is analyzed. The possibility of partial detonation failure with subsequent initiation is shown when the diffracted wave is reflected from the wall of the wide part of the channel with further unification of the shock wave and combustion front.

In [6], a physico-mathematical model and technology for numerical calculations of shock-wave and detonation processes in heterogeneous mixtures of gas and small reacting particles in channels of complex geometry are proposed. The processes of propagation of shock and detonation waves in gas suspensions of aluminum particles in oxygen in a flat channel with sudden expansion are investigated. It is revealed that when detonation waves exit from the narrow part of the channel, various variants of the flow development are possible from continuous propagation to complete disruption of heterogeneous detonation, as well as partial disruption with subsequent re-initiation. The influence of particle size and geometric parameters on the process has been established.

In [4, 5], the output of detonation waves from a flat channel into a region with a linear expansion of the channel cross-section is considered. The process of transition of the detonation wave into an expanding section and further propagation is analyzed. Numerical results of the flow at different angles of expansion are given. Three modes of detonation propagation have been established: for critical, critical and subcritical, found earlier in [1, 6].

In [3, 8] the results of a numerical study of the patterns of propagation of detonation waves in mono- and polydisperse (two-fraction) gas suspensions of

unitary fuel in sharply expanding pipes are presented. A comparative analysis of the effect of mono- and polydispersity of unitary fuel particles on the attenuation of detonation waves is carried out. The dependencies of the critical ratio of the pipe diameters of a composite pipeline on the relative mass content and polydispersity of particles of different sizes are given.

In this paper, which is a logical continuation of [3, 8] the results of the influence of the diameter and spatially inhomogeneous distribution of the concentration of particles of unitary fuel on the reduction of the maximum pressure on the wall are presented.

2. Statement of the problem

The system of differential equations governing the time-dependent, two-dimensional, axisymmetric flow of a monodisperse gas suspension can be represented in the following form [3, 7, 9].

Mass conservation equations:

$$\begin{aligned} \frac{\partial \rho_1}{\partial t} + \frac{1}{r} \frac{\partial (\rho_1 v_{1,r} r)}{\partial r} + \frac{\partial (\rho_1 v_{1,z})}{\partial z} &= J_{21}, \\ \frac{\partial \rho_2}{\partial t} + \frac{1}{r} \frac{\partial (\rho_2 v_{2,r} r)}{\partial r} + \frac{\partial (\rho_2 v_{2,z})}{\partial z} &= -J_{21}. \end{aligned} \quad (1)$$

Equations of conservation of mass for an inert gas and the gaseous products of combustion of a gas mixture:

$$\begin{aligned} \frac{\partial \rho_{11}}{\partial t} + \frac{1}{r} \frac{\partial (\rho_{11} v_{1,r} r)}{\partial r} + \frac{\partial (\rho_{11} v_{1,z})}{\partial z} &= 0, \\ \frac{\partial \rho_{12}}{\partial t} + \frac{1}{r} \frac{\partial (\rho_{12} v_{1,r} r)}{\partial r} + \frac{\partial (\rho_{12} v_{1,z})}{\partial z} &= J_{21}. \end{aligned} \quad (2)$$

Equations of conservation of the number of dispersed particles:

$$\frac{\partial n_2}{\partial t} + \frac{1}{r} \frac{\partial (n_2 v_{2,r} r)}{\partial r} + \frac{\partial (n_2 v_{2,z})}{\partial z} = 0, \quad \alpha_2 = \frac{1}{6} \pi d_2^3 n_2. \quad (3)$$

Phase momentum conservation equations:

$$\begin{aligned}
 \frac{\partial(\rho_1 v_{1,r})}{\partial t} + \frac{1}{r} \frac{\partial(\rho_1 v_{1,r} v_{1,r} r)}{\partial r} + \frac{\partial(\rho_1 v_{1,r} v_{1,z})}{\partial z} + \frac{\partial p}{\partial r} &= -F_{2,r} + J_{21} v_{2,r}, \\
 \frac{\partial(\rho_1 v_{1,z})}{\partial t} + \frac{1}{r} \frac{\partial(\rho_1 v_{1,r} v_{1,z} r)}{\partial r} + \frac{\partial(\rho_1 v_{1,z} v_{1,z})}{\partial z} + \frac{\partial p}{\partial z} &= -F_{2,z} + J_{21} v_{2,z}, \\
 \frac{\partial(\rho_2 v_{2,r})}{\partial t} + \frac{1}{r} \frac{\partial(\rho_2 v_{2,r} v_{2,r} r)}{\partial r} + \frac{\partial(\rho_2 v_{2,r} v_{2,z})}{\partial z} &= F_{2,r} - J_{21} v_{2,r}, \\
 \frac{\partial(\rho_2 v_{2,z})}{\partial t} + \frac{1}{r} \frac{\partial(\rho_2 v_{2,r} v_{2,z} r)}{\partial r} + \frac{\partial(\rho_2 v_{2,z} v_{2,z})}{\partial z} &= F_{2,z} - J_{21} v_{2,z}.
 \end{aligned} \tag{4}$$

Equations of heat inflows to particle phases:

$$\frac{\partial(\rho_2 e_2)}{\partial t} + \frac{1}{r} \frac{\partial(\rho_2 e_2 v_{2,r} r)}{\partial r} + \frac{\partial(\rho_2 e_2 v_{2,z})}{\partial z} = Q_{12} \eta (-J_{21}) - J_{21} e_2. \tag{5}$$

Equations of conservation of the total energy of the mixture:

$$\sum_{i=1}^3 \left[\frac{\partial(\rho_i E_i)}{\partial t} + \frac{1}{r} \frac{\partial(\rho_i E_i + \alpha_i p) v_{i,r} r}{\partial r} + \frac{\partial(\rho_i E_i + \alpha_i p) v_{i,z}}{\partial z} \right] = 0, \tag{6}$$

$$\rho_{11} = \rho_{11}^0 \alpha_{11}, \rho_{12} = \rho_{12}^0 \alpha_{11}, \rho_1 = \rho_1^0 \alpha_1, \rho_1^0 = \sum_{k=1}^2 \rho_{1k}^0, \rho_1 = \rho_{11} + \rho_{12},$$

$$\rho_2 = \alpha_2 \rho_2^0,$$

$$\rho_3 = \alpha_3 \rho_3^0, v_i^2 = v_{ir}^2 + v_{iz}^2, \alpha_1 + \alpha_2 + \alpha_3 = 1, E_i = e_i + 0.5 v_i^2,$$

$$(i = 1; 2).$$

The indices "1" and "2" at the bottom refer respectively to the parameters of the gas mixture and particles of the unitary fuel. The mean and actual densities, the volume content, the mass velocity, and the specific and total energies of phase i are denoted as $\rho \rho_i, \rho_i^0, \alpha_i, v_i, e_i$ and E_i respectively ($i = 1, 2$); ρ_{11}, ρ_{12} and ρ_{11}^0, ρ_{12}^0 are average and true densities of the gas phase components; v_{ir} and v_{iz} are the components of the velocity v_r ; the parameters n_2 and d_2 are the number density and the current size of the monofuel particles; p is the pressure of the gas mixture; $F_{2,r}$ and $F_{2,z}$ are the components of the interfacial friction force; Q_{12} is the intensity of heat exchange between the gas and dispersed phases; J_{21} is the intensity of volumetric injection of gaseous products of the chemical reaction of combustion of particles of unitary fuel; η is the unit Heaviside function.

3. Formulation of the problem

We consider a simple pipeline made of pipes of diameters D_1 and D_2 (Fig. 1) filled with a homogeneous monofuel-air mixture. The left end of the pipe ($z = 0$) is closed, and the right end ($z = L$) is open. At the initial time, a perturbation of the gas in the form of a triangular shock wave is produced at the left end of the pipe in region 0, which ignites the monofuel-air mixture in region 1 of the narrow part of the pipeline. Given sufficient energy of the initiating shock wave, it is required to model the explosion of the air-fuel mixture in such a way that of a stationary heterogeneous detonation wave forms in the narrow pipeline region and then passes to the wide region 2 of the pipeline. It is required to study the effect of shielding layers of homogeneous or inhomogeneous gas suspension on reducing the maximum pressure on the barrier wall behind the reflected detonation waves.

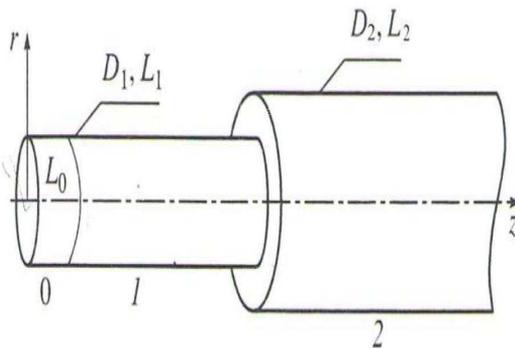


Fig. 1. Diagram of a simple pipeline: L_i and D_i are the length and inside diameter of the i -th section ($i = 1, 2$) of the pipeline; 0 is the region of shock initiation in the gas of length $L_0 = z_f$, 1 and 2 are the pipeline regions filled with the air-powder mixture, having length $L_1 = Z_* - L_0$ and $L_2 = Z_{**} - (L_0 + L_1)$, respectively; Z_* is the axial coordinate of the place of sudden expansion of the pipeline.

The initial and boundary conditions of the problem are similar to those specified in [7].

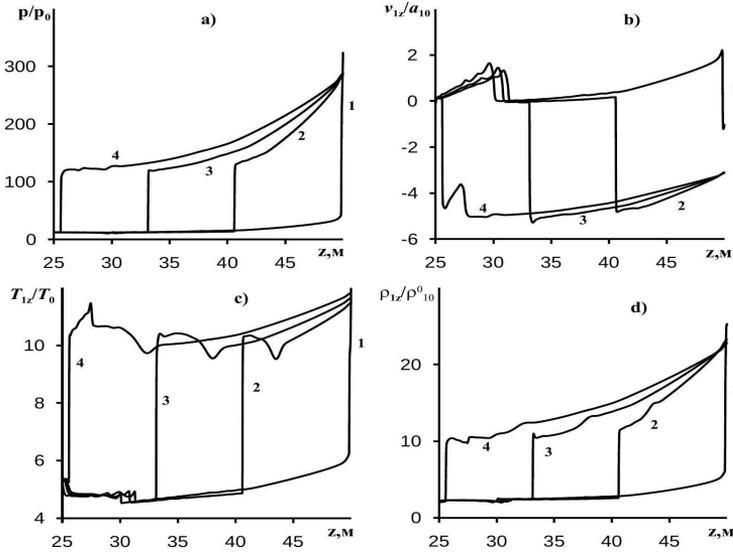
The problem was solved numerically by the method of large particles [2]. The calculations were performed for mixtures of air and powder particles.

All calculations were carried out for a length of the initiating shock wave $z_f = 0.4$ m. In the main series of calculations, it was assumed that the Mach number of the shock wave $M_0 = 9$. The initial particle diameter (d_2) was varied in the range $3 \leq d_2 \leq 30 \mu\text{m}$, and the mass content of the particles ($m_2 = \rho_{20}/\rho_{10}$) in the range $0.5 \leq m_2 \leq 2$. The coordinates z_f , z_* , and z_{**}

were set equal to 0.4, 25 and 50 m. The radius of the narrow portion of the pipe is varied in the range of $0.04 \leq R_1 \leq 0.1$ m, and the radius of its wide range, in the range of $0.08 \leq R_2 \leq 0.3$ m.

4. Calculation results

It is of interest to consider the case of interaction of a passing detonation wave in gas suspensions of a unitary fuel with an obstacle. The process of reflection of detonation waves from a rigid wall is illustrated in Fig. 2, which shows the calculated profiles of pressure (a), mass velocity (b), temperature (c) and density (d) of the gas mixture at time $t = 38.3, 43.5; 47.05, 50.6$ ms. The diameter of the monofuel particles was $d_2 = 30 \mu\text{m}$, and the initial relative mass content of particles in the mixture was $m_2 = 2$. The radius of the narrow part of the pipeline is $R_1 = 0,1$ m, and the radius of its wide part is $R_2 = 0,3$ m. When interacting with the barrier of the incoming pulse, a reflected detonation wave is formed. The pressure behind the detonation wave reflected from the barrier is higher than the pressure in the incident wave. The velocities of the gas and particles of the unitary fuel behind the reflected detonation wave are significantly less than the velocities of the phases in the incident wave. Over time, the detonation wave reflected from the barrier first slows down the gas flow running into the wall, and then involves it in the reverse movement from



the wall.

Fig. 2. Profiles of pressure (a), mass velocity (b), temperature (c) and density (d) of the gas mixture after reflection of detonation waves from a rigid wall at

time points $t = 38.3, 43.5; 47.05,$

50.6 ms. $m_{20} = 2; d_{20} = 30\mu\text{m}; R_1 = 0, 1 \text{ m}, R_2 = 0, 3 \text{ m}.$

Figure 3 shows the corresponding Fig. 2 characteristic profiles of the average density and velocity of particles of unitary fuel on the axis of symmetry at time $t = 37.95; 38.14; 38.28; 38.33$ ms. Curve 1 corresponds to the value of the average density of particles of unitary fuel before reflection from the barrier. The average particle density of the unitary fuel decreases on the barrier wall and over time is almost zero.

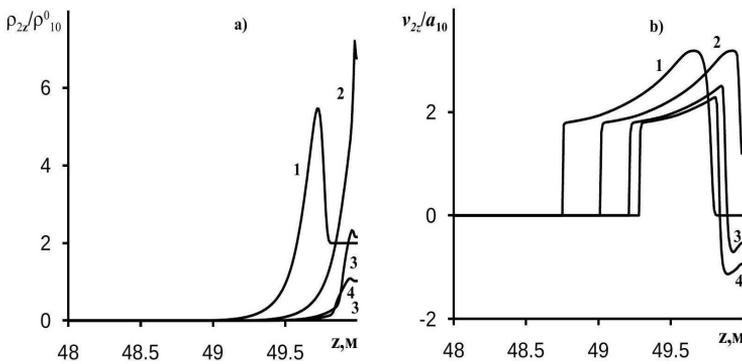


Fig. 3. Profiles of average density (a) and velocity (b) of unitary fuel particles after reflection of detonation waves from a rigid wall at time points $t = 37.95; 38.14; 38.28; 38.33$ ms; $m_{20} = 2; d_{20} = 30\mu\text{m}; R_1 = 0, 1 \text{ m}, R_2 = 0, 3 \text{ m}.$

Fig. 4 shows the envelopes of the maximum pressures behind combustion waves on the axis of symmetry in the wide part of the pipeline. Curve 1 corresponds to particles with a diameter of $d_{20} = 3\mu\text{m}$, curve 2 with a diameter of $d_{20} = 15\mu\text{m}$. The mass content of the particles is equal $m_{20} = 0.5$. From the graphs it can be seen that the particle sizes of the unitary fuel qualitatively affect the structures of detonation waves. A decrease in the particle diameter leads to strong pressure fluctuations. With fixed parameters of the pipeline and the gas suspension for particles with a diameter of $d_{20} = 3\mu\text{m}$, continued detonation is observed, and for particles with a diameter of $d_{20} = 15\mu\text{m}$, detonation failure is observed in a wide part of the pipeline.

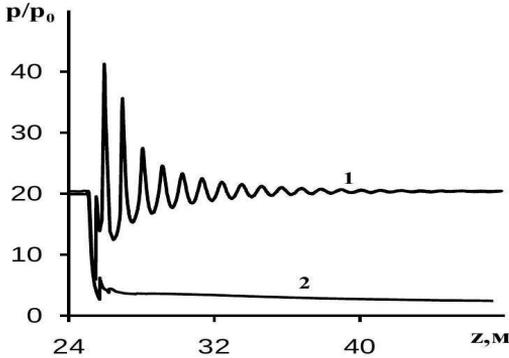


Fig. 4. Envelopes of maximum pressures behind combustion waves on the axis of symmetry in the wide part of the pipeline. $m_{20} = 0.5$, $R_1 = 0.1$ m, $R_2 = 0.3$ m. Curve 1 corresponds to: $d_{20} = 30\mu\text{m}$, curve 2: $d_{20} = 15\mu\text{m}$.

Some integral results of numerical investigation of the effect of the particle size of unitary fuel in the shielding layers of a monodisperse gas suspension on the maximum pressure on the barrier walls behind the reflected detonation waves are shown in Fig. 5. Curve 1 illustrates the dependence of peak pressure for particles with a diameter $d_{20} = 3\mu\text{m}$, curve 2 corresponds to particles with a diameter $d_{20} = 15\mu\text{m}$. When $0 < m_{20} < 0.8$ the maximum pressure on the wall is less for particles with a diameter $d_{20} = 15$ than $d_{20} = 3$, this is explained by the fact that at $d_{20} = 15\mu\text{m}$ a damping wave is formed on the wall (see Fig. 4, curves 2).

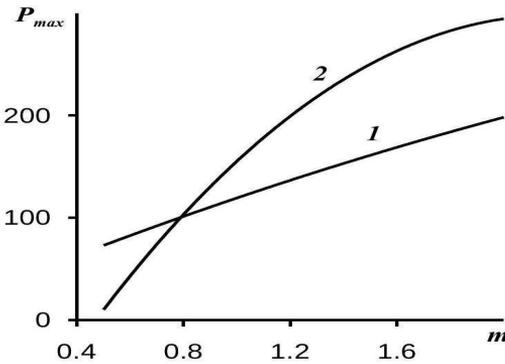


Fig. 5. Dependence of the maximum pressure on the wall on the relative mass content of particles of unitary fuel. Curve 1 corresponds to: $d_{20} = 3\mu\text{m}$, curve 2: $d_{20} = 15\mu\text{m}$. $R_1 = 0.1$ m, $R_2 = 0.3$ m.

Fig. 6 shows the envelopes of the maximum pressures behind combustion waves on the axis of symmetry in the wide part of the pipeline. The diameter of the particles of the unitary fuel is $d_{20} = 15\mu\text{m}$, the initial relative mass

content of particles in the mixture in the narrow part of the pipeline $m_{20} = 1$, in the wide part of the pipeline are determined, with a linearly increasing law of change in the concentration of particles $\rho_2(z, 0) = Az - B, A = 0,08; B = 2$; and a linearly decreasing law of change in the concentration of particles $\rho_2(z, 0) = Az + B, A = -0,08, B = 4; 25 < z \leq 50$. The radius of the narrow part of the pipeline is $R_1 = 0,1$ m, and the radius of its wide part is $R_2 = 0,3$ m. The solid lines correspond to the case of detonation wave propagation through a homogeneous gas suspension. Dashed lines correspond to linearly decreasing, dashed lines correspond to linearly increasing laws of change in the initial concentration of particles. With fixed parameters of the pipeline and gas suspension with a homogeneous and linearly increasing law of change in the initial concentration of particles, a continuation of detonation is observed, and with a linearly decreasing one, a gradual breakdown of detonation is observed in a wide part of the pipeline.

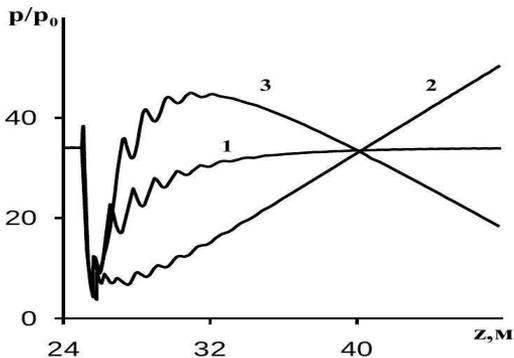


Fig. 6. Envelopes of maximum pressures behind combustion waves on the axis of symmetry in wide parts of the pipeline. $d_{20} = 15\mu\text{m}, m_{20} = 1, R_1 = 0,1$ m, $R_2 = 0,3$ m. Curve 1— corresponds to a homogeneous, 2 - linearly increasing, 3 - linearly decreasing law of concentration of particles of unitary fuel.

The results of a numerical study of the effect of the distribution law of the initial concentration of unitary fuel particles in the shielding layers of a monodisperse gas suspension on the maximum pressure on the barrier walls behind the reflected detonation waves are shown in Fig. 7. Curve 1 illustrates the dependence of the peak pressure on the barrier walls on the relative mass content of unitary fuel particles in layers of homogeneous gas suspension with a zero gradient of the dimensionless average density of unitary fuel particles, 2 and 3 are similar dependencies for layers of gas suspension, respectively, with linearly increasing and linearly decreasing particle distribution laws.

According to Fig. 7, the maximum value of the gas pressure on the wall

monotonically increases with an increase in the relative mass content of the suspension.

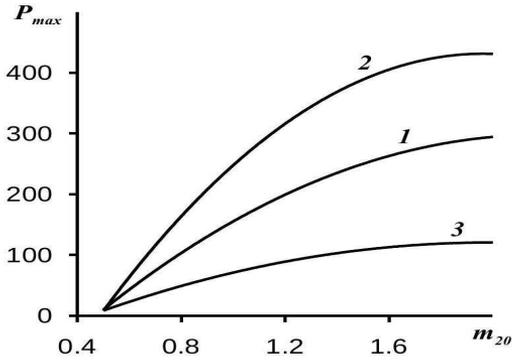


Fig. 7. Dependence of the maximum gas pressure on the wall on the relative mass content of particles of unitary fuel. Curve 1- corresponds to a homogeneous, 2 - linearly increasing, 3 linearly decreasing law of concentration of particles of unitary fuel. $d_{20} = 15\mu\text{m}$, $m_{20} = 1$, $R_1 = 0.1$ m, $R_2 = 0.3$ m.

5. Conclusion

The conducted research indicates a significant influence of the particle size of the unitary fuel on the reduction of the maximum pressure on the wall during the propagation of a wave of heterogeneous detonation in a wide part of the pipeline.

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