ON THE STABILITY OF COMBUSTION OF POROUS EXPLOSIVES

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Abstract

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ON THE STABILITY OF COMBUSTION OF POROUS EXPLOSIVES

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The burning rate of powdered and porous explosives (E.V.) increases sharply when the pressure is raised above a certain critical pressure of "breakdown" of the normal combustion regime ([1,2]). The phenomenon of breakdown of the normal combustion regime is usually associated with the breakthrough of hot combustion products into the pores of the explosive under the action of the so-called dynamic pressure increase above the burning surface ([1,2]).

Normal flame propagation is possible if the characteristic size of the surface irregularities δ is substantially smaller than the effective width of the combustion zone l ($\delta \ll l$). If the size of the surface irregularities exceeds the effective width of the chemical-reaction zone ($\delta > l$), then the linear velocity of flame propagation may considerably exceed the normal burning rate, since combustion takes place over the large area of the irregularities and pores. A qualitative consideration of this question was carried out in ([2]). The critical condition for breakdown of the normal combustion regime may be written as follows:

$$\delta/l = b = \text{const.} \tag{1}$$

The constant b may depend on the form and character of the irregularities and on the properties of the explosive. Substituting the expression for the width of the combustion zone from ([3]) into equality (1), we obtain the condition for breakdown of the normal combustion regime

$$\frac{\delta \rho u c_p}{\lambda} = \frac{\delta B P^{\nu} c_p}{\lambda} = b, \tag{2}$$

where ρu is the mass burning rate; P is the pressure; B, ν are constants; c_p is the heat capacity; λ is the coefficient of thermal conductivity.

If the substance under study has through pores, then the magnitude of the irregularities can be determined from the porosity m and permeability k: $\delta = d\sqrt{k/m}$. The quantity d depends only weakly on the shape of the pores ([4]) (for the so-called ideal soil). Now condition (1) takes the form

$$\sqrt{\frac{k}{m}}\,\frac{\rho u c_p}{\lambda} = \sqrt{\frac{k}{m}}\,\frac{BP^{\nu} c_p}{\lambda} = \frac{b}{d}. \tag{3}$$

The burning rate and pressure at which breakdown of the normal combustion regime occurs are equal to

$$(\rho u)_{\mathrm{cr}} = \frac{\lambda b}{\rho c_p} = \frac{\lambda b}{c_p d}\sqrt{\frac{m}{k}}, \qquad P_{\mathrm{cr}} = \left(\frac{\lambda \delta b}{c_p B}\right)^{1/\nu} = \left(\frac{\lambda b}{c_p B d}\sqrt{\frac{m}{k}}\right)^{1/\nu}. \tag{4}$$

It follows that an increase in the burning rate and in the pore sizes facilitates breakdown of the normal combustion regime, which is in qualitative agreement with experiment ([1,2]).

It is physically clear that intense pressure oscillations promote the penetration of hot gases into the pores of an explosive charge burning at velocity u. To study this phenomenon we shall use the one-dimensional equations of motion and continuity of a gas in a porous medium

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}\right) = -\frac{\partial p}{\partial x} - \frac{m\mu}{k}v,$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0, \tag{5}$$

where x is the coordinate; t is time; μ is the viscosity coefficient; v is the velocity of gas motion. The boundary conditions are: $P = P_1 \cos\omega t + P_0$ at $x = ut$; $P = P_0$ at $x = -\infty$.

We shall solve the problem for small changes in the pressure and density of the gas. For an exact solution of the problem it is also necessary to write down the equation of state of the gas and the law of heat and mass exchange of the gas with the surrounding medium. For simplicity we shall restrict ourselves to the cases of polytropic and isothermal filtration. Generally speaking, at variable pressure the burning rate will be variable, but for the time being we shall not take this into account.

In the limiting case, when the viscous forces considerably exceed the inertial forces, we obtain the following criterion for penetration of gases into the burning substance:

$$\frac{P_1}{P_0}\sqrt{\frac{N}{2}} \geqslant 1 \tag{6}$$

for $\sqrt{N} \gg 1$ and $M^4 N^2 \ll 1$. Here $M = u/a$, where a is the speed of sound in the filtering gas; $N = 2\omega a^2 \rho_0 k / u^2 m\mu$, where ω is the oscillation frequency, ρ_0 is the mean gas density. In the isothermal regime $N = 2\omega P_0 k/u^2 m\mu$. It is evident that an increase in the amplitude and frequency of the oscillations promotes the breakthrough of gases into the pores of the explosive (all other conditions being equal, relation (6) has the form

$$\frac{P_1}{P_0}\sqrt{\omega} \geqslant \text{const.}$$

)

The penetration of gases substantially affects burning when the gases penetrate sufficiently deeply, to a depth S. This quantity S must be proportional to the characteristic width of the heated layer l. The proportionality coefficient must depend on the conditions of heat exchange and of ignition of the explosive. Apparently this proportionality coefficient increases as the permeability and porosity of the explosive decrease.

The order of magnitude of the depth of gas penetration S into the burning substance is equal to $S \simeq \frac{2\pi}{\omega}(v-u)$. Let us write the condition for gas penetration to a depth S:

$$\frac{P_1}{P_0}\sqrt{\frac{N}{2}} \geqslant 1 + \frac{S\omega}{2\pi u}. \tag{7}$$

The minimum oscillation amplitude $(P_1/P_0)_{\min}$ necessary for gas penetration to a depth S is attained at the frequency ω_1:

$$\omega_1 = \frac{2\pi u}{S}, \qquad \left(\frac{P_1}{P_0}\right)_{\min} = \frac{2\sqrt{2}}{\sqrt{N(\omega_1)}}.$$

If $S = l$, then

$$\left(\frac{P_1}{P_0}\right)_{\min} = \sqrt{\frac{x m\mu}{2\pi P_0 k}}, \qquad \omega_1 = \frac{2\pi u^2}{x},$$

where x is the thermal diffusivity coefficient of the explosive. The period of oscillations most dangerous for gas penetration to the depth of the heated layer is approximately equal to the relaxation time of the thermal layer of the burning explosive.

At each pressure P_0 there exists an optimal oscillation frequency ω_1, most favorable for disrupting the regime of normal combustion. The physical meaning of the existence of an optimal frequency is that an increase in frequency facilitates the penetration of gas into the burning substance, but at too high a frequency the gas penetrates only into a thin surface layer of the explosive.

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Note: Figure translations are in progress. See original paper for figures.