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REGULARITIES OF THE CHANGE IN THE CRITICAL COMBUSTION THICKNESS FOR POROUS LOW-GAS PYROTECHNIC SPECIMENS

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Experimental results on the regularities of the change in the critical combustion thickness as a function of the compaction coefficient and the thickness of the inert envelope are presented. In accordance with existing views, it is established empirically that the product of the critical combustion thickness, the adiabatic rate, and a linear function of density is constant. Exact expressions are obtained for the characteristic equation of the fourth degree and for the temperature of the combustion front of the double-layer system of gasless mixture—inert plate, which, for limiting cases, coincide with solutions of Ya. B. Zel'dovich and G. P. Ivleva, A. G. Merzhanov, and B. V. Shkadinskii.

Miniaturization of auxiliary facilities of rocket-space technology [1, 2] leads, in combustion, to enhancement of heat transfer between pyrotechnic mixtures and materials contacting them. In particular, low-gas and gasless mixtures employed in the form of a thin layer that provides specified heating of plates between which layer 2 is located (Fig. 1) are currently widely used. In miniaturization of pyrotechnic devices, the forces of compaction (pressing) of pyrotechnic mixtures are increased and the thickness of contacting structural elements of the above-mentioned devices, manufactured from various matertials, is reduced. With compaction of the porous mixtures and a decrease in the layer thickness, critical conditions of combustion can be attained, viz., impossibility of the existence of a self-propagating combustion front. The aim of the present paper is to experimentally study the regularities of the change in the critical combustion thickness as a function of the compaction coefficient (the pressing force) and the thickness of the contacting envelope, as well as to compare the obtained results with theoretical concepts.

For the investigations we used a familiar low-gas pyrotechnic mixture of zirconium and barium chromate with a fibrous inorganic binder. The compaction coefficient is equal to the ratio of the density of the porous material to its maximum density [2]. The dependence of the critical combustion thickness on the compaction coiefficient and the thickness of the contacting metal plates was determined using special compacting and heat-removing elements [3, 4], which are plates with lateral surfaces made in the form of sections of helical surfaces. Using the above elements permitted a practically continuous change in the compaction coefficient and the thickness of the contacting plate within the required limits.

Figure 1 shows a schematic of the facility for determining the critical combustion thickness as a function of the compaction coefficient. Wedge-like specimen 2 is located between bars 1, whose surfaces contacting the specimen are made helical.

Axes 3 of the helical surfaces and the vertex line of wedge-like specimen 2 are aligned. Therefore, when the specimen is pressed between the bars, the compaction coefficient is a function of two coordinates. The direction of one coordinate coincides with that of the axes of the helical surfaces, and the other is perpendicular to the first one. The specimen bottom is ignited, and after cessation of combustion the extinction line is determined. The error in determining the critical thickness is not greater than 2%.

Figure 2 illustrates a facility for determining the critical combustion rate as a function of the thickness of the metal foil. Pyrotechnic specimen 1 was placed in the symmetry plane of heat sensor 2 (see Fig. 3) and pressed

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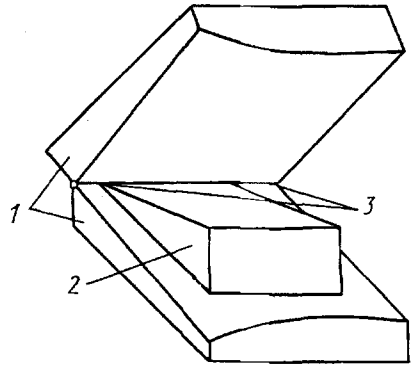


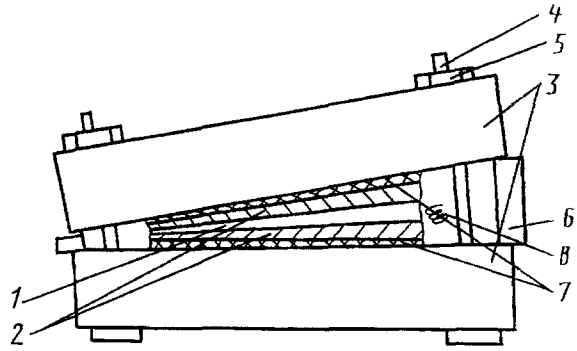
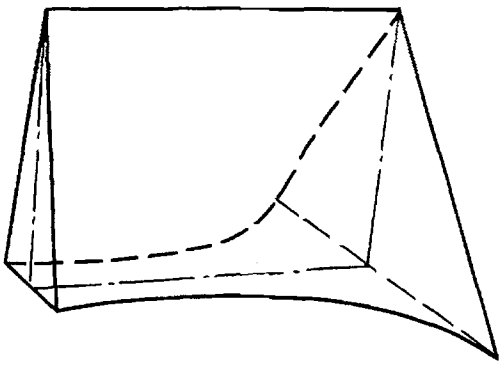


Fig. 1. Device for determining the critical combustion thickness as a function of the compaction coefficient.

Fig. 2. Scheme of measuring the critical combustion thickness: 1) tested specimen; 2) heat sensor; 3) bars; 4) bolt; 5) nut; 6) thickness gauge; 7) asbestos spacer; 8) Nichrome spiral.



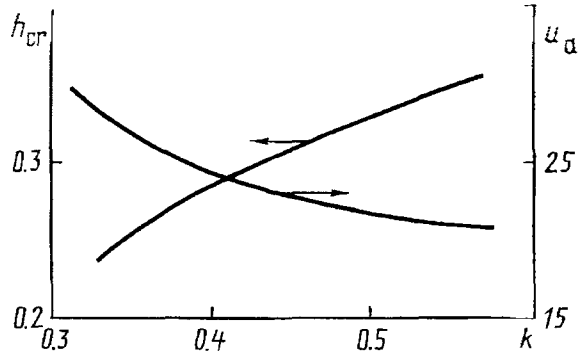


Fig. 3. Heat sensor.

Fig. 4. Critical combustion thickness h_{cr}, mm, and combustion rate u_a, mm/sec, as functions of the compaction coefficient k.

to a preset compaction coefficient by bars 3, separated from the heat sensor by heat insulating asbestos spacers. Thereby, a two-coordinate change in the heat transfer between the specimen and the plates was ensured. The specimen-to-plate thickness ratio in the direction perpendicular to the axis of the helical surface is constant, whereas in the direction parallel to the axis it varies continuously within the required limits. The ignition by spiral 8 was effected at the specimen bottom and, after the combustion ceased, the extinction line was plotted on the graph of the critical combustion thickness vs the plate thickness.

Measurement results for the critical combustion thickness in the device depicted in Fig. 1 are given in Fig. 4, which also presents measurement results for the adiabatic combustion rate at various compaction coefficients. To facilitate the measurements, the adiabatic combustion rate was determined in the combustion of specimens whose thickness and width greatly exceeded the corresponding critical dimensions. It is evident from Fig. 4 that, with increasing compaction coefficient, the combustion rate decreases and the critical thickness rises.

The critical combustion thickness is generally assumed to be proportional to the characteristic thickness of the heated layer under adiabatic conditions, that is,

$$h_{cr} = A\frac{\kappa}{u_a} = A\frac{\lambda}{\rho c u_a},$$

where A is a characteristic constant, λ, ρ, and c are the thermal conductivity, density, and specific heat, and u_a is the adiabatic combustion rate.

The thermal conductivity of heterogeneous systems may be represented in the form [5]

$$\lambda = \lambda_0 \left[1 - \frac{1-k}{\frac{1}{1-\nu} - \frac{k}{3}} \right],$$

where λ_0 is the thermal conductivity of the frame and ν is the ratio between the thermal conductivities of the gas confined in the pores and the solid frame. For the specimens employed, $\nu \approx 10^{-2}$; hence $\lambda \approx \lambda_0 \cdot 2k/3-k$, and from the above equations we can derive the following relation:

$$h_{cr} u_a (3-k) = 2A \frac{\lambda_0}{\rho_{max} c}$$

whose right side is independent of the compaction coefficient and equals 19 ± 3 km^2/sec for the specimens used.

Study [7] theoretically investigated the regularity of the change in the critical combustion thickness in accordance with the envelope thickness with equality of their thermal diffusivities. For the specimens we used the thermal diffusivity of the envelope is appreciably higher, and therefore, similarly to [7], we considered the equations

$$\lambda_1 \frac{d^2T_1}{dx^2} - \rho_1 c_1 u \frac{dT_1}{dx} - \frac{\alpha}{h}(T_1 - T_2) = 0,$$

$$\lambda_2 \frac{d^2T_2}{dx^2} - \rho_2 c_2 u \frac{dT_2}{dx} - \frac{\alpha}{\delta}(T_1 - T_2) = 0$$

with the boundary conditions

$$x = -\infty; \quad T_1 = T_2 = T_0; \quad x = +\infty; \quad \frac{dT_1}{dx} = \frac{dT_2}{dx} = 0$$

and the conditions of cross-linking in the combustion front

$$T_i(-0) = T_i(+0); \quad \lambda_i \frac{dT_i}{dx}\Big|_{x=-0} - \lambda_i \frac{T_i}{dx}\Big|_{x=+0} = \begin{cases} \rho_i uQ, & i = 1, \\ 0, & i = 2, \end{cases}$$

where λ_i, ρ_i, and c_i are the thermal conductivity, density, and specific heat; T_0 is the initial temperature; subscripts 1 and 2 denote the mixture layer and the plate of thicknesses h and δ, respectively; Q is the thermal effect; and $\alpha \sim \lambda_i/h$ is the heat transfer coefficient.

Exact expressions are obtained for the characteristic equation and the temperature of the combustion front in dimensionless variables:

$$k = \frac{\lambda_2 \rho_1 c_1}{\lambda_1 \rho_2 c_2}; \quad P = \frac{\rho_2 c_2}{\rho_1 c_1}; \quad \Phi = P\frac{\delta}{h}; \quad b = \frac{\alpha \lambda_1}{h \rho_1^2 c_1^2 u^2}; \quad \theta_1 = \frac{T_1 - T_0}{Q/c},$$

$$\Phi(z)(z-1)(kz-1) - b(z-1) - b\Phi(kz-1) = 0,$$

$$\Theta_1(0) = \frac{(z-1)(1 + 2bk/\Phi - kz)}{k[b(k + 1/\Phi) - 1]z^2 + [k + 1 - b(k^2 - 2k - (2k-1)/\Phi]z - 1 - 2b(1 + k/\Phi)},$$

which, for the case of heat removal at a constant wall temperature, correspond to $\Phi \to \infty$ and $b/k \sim 0$ and coincide with familiar expressions [6], and, for $k = 1$, with data of [7].

For the considered case $k \gg 1$ we derived an approximate relation for the critical combustion thickness

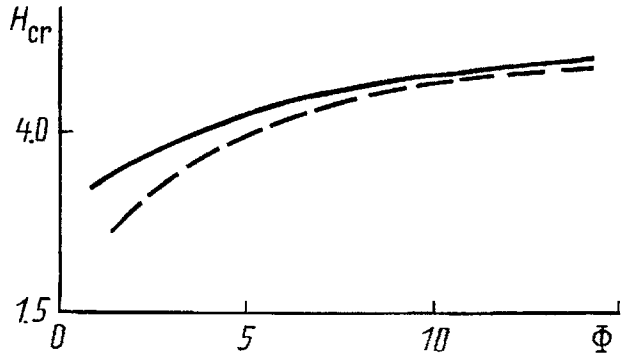


Fig. 5. Dimensionless critical combustion thickness vs the parameter Φ: dashed line indicates theoretical prediction and solid line, experimental regularity.

$$H_{cr} = 2\sqrt{\left(\frac{\varepsilon \exp\left[1 - \varepsilon/\Phi\,(1 + \gamma + 1/\Phi)\right]}{1 + \gamma + 1/\Phi}\right)},$$

$$\varepsilon = E/2R\,(T_0 + Q/c); \quad \gamma = c_1 T_0/Q; \quad H_{cr} = k_0 \frac{h_{cr} u_a \rho_1 c_1}{\lambda_1},$$

where $k_0 \approx 1$ and ε is the dimensionless activation energy.

The latter relation is verified experimentally using the device shown in Figs. 2 and 3 at a compaction coefficient of 0.4. Preliminary investigations established that the combustion temperature is 2110 ± 120 K, the activation energy is 27.0 ± 3.8 kcal, the mass fraction of the condensed phase is larger than 0.95, and the combustion heats under adiabatic and nonadiabatic conditions are practically identical. Hence, the assumptions of [7] are valid for the specimens used.

It is seen from Fig. 5 that the theoretical and experimental results are in favorable agreement. It is noteworthy that, with small envelope thickness, the measurement results are affected by heat losses to the heat-insulating material.

The established regularity permits purposeful modernization of various devices.

NOTATION

h_{cr}, H_{cr}, critical combustion thickness (dimensional and dimensionless); A, characteristic constant; λ, thermal conductivity; ρ, density; c, specific heat; u_a, adiabatic combustion rate; T_0, initial temperature; Q, thermal effect; α, heat transfer coefficient; ε, dimensionless activation energy.

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