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Figure 1. Dependence of burning rate on pressure at different oxidizer particle sizes for a stoichiometric mixture of $KClO_4$ with bitumen. 1 –$d = 0.01$ mm; 2 –0.07 mm; 3 –0.2 mm; 4 –1.7 mm

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Abstract

Full Text

Physical Chemistry

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The Influence of Particle Size on the Burning Rate of Mixtures Based on $KClO_4$

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The question of the dependence of the burning rate of systems consisting of a mechanical mixture of fuel and oxidizer on particle size was theoretically considered by O. I. Leipunsky ([1]) using the combustion of black powder as an example. Leipunsky came to the conclusion that, in the diffusion region, the burning rate u should be inversely proportional to particle size, $u \sim 1/d$. Novozhilov ([3]) arrived at an analogous conclusion.

Fig. 1. Dependence of the burning rate on pressure at different oxidizer particle sizes for a stoichiometric mixture of $KClO_4$ with bitumen.
1 –$d = 0.01$ mm; 2 –0.07 mm; 3 –0.2 mm; 4 –1.7 mm.

In the present work, preliminary experimental results are presented on the dependence of the burning rate of heterogeneous systems, in which both components are initially in the solid phase, on the degree of heterogeneity. The latter depends on the particle size of both components (as well as on the volume ratio between the components, the degree of mixing, and the relative density of the charge, which, however, may be disregarded if they are kept constant for the given system). In the particular case where one of the components is taken as a narrow particle-size fraction (with mean size d), and the second component is plastic at the moment the charge is prepared, or has a particle size much smaller than d, or passes into the gas phase much more readily than the first component, the degree of heterogeneity is determined by a single parameter d.

We investigated in greatest detail the dependence $u(d)$ for mixtures of crystalline $KClO_4$ and fuels that were plastic at the time the charge was prepared (bitumen, tar, Plexiglas). Three narrow sieve fractions of $KClO_4$ and one frac-

Figure 2

Figure 2: Figure 2

tion obtained in a vibratory mill were taken, with mean microscopic diameters $d = 1.7$; 0.2; 0.07 and ~ 0.01 mm. The mixture of $KClO_4$ with the fuel, preliminarily diluted with solvent, was kept on a vibrating platform while being stirred, and then dried in a water bath and in a drying oven. The finished mixture was pressed to a relative density* $\delta = 0.98$–1.00 in the case of bitumen and tar, and $\delta = 0.90$ in the case of Plexiglas. To the resulting pellets (6 mm in diameter and 8-10 mm high), longitudinal halves of a glass tube were glued on both lateral sides by means of a thin film of water glass with filler. The mixture with tar, which was highly plastic, was pressed into thick-walled glass tubes. The burning rate was measured with a photorecorder in a 2-liter bomb in a nitrogen atmosphere at $0 \leqslant p \leqslant 125$ atm.

Fig. 2. Dependence of the burning rate on oxidizer particle size for a stoichiometric mixture of $KClO_4$ with bitumen.
1 $-p = 1$ atm; 2 -3 atm; 3 -5 atm; 4 -10 atm

In the present work we shall consider only the regime of uniform layer-by-layer burning. Breakdown of this regime ("jump" of the flame) occurs when the relative density of the charge is sufficiently reduced (for the given p). For the plastic mixture with tar, at high p, a regime of disturbed burning was observed, in which the dependence $u(p)$ was considerably stronger than in the region of layer-by-layer burning; moreover, the burning rate did not decrease but, on the contrary, increased with increasing d.

Figure 1 gives the dependence of the burning rate on pressure for a stoichiometric mixture of bitumen with $KClO_4$ at different oxidizer particle sizes. The role of particle size is revealed more clearly in Fig. 2, where the dependence of u on d at various pressures is given directly. It is evident that the dependence $u(d)$ is not simple: the corresponding curves have an S-shaped form.

At sufficiently small particle sizes ($d \leqslant d_{\text{min}}$), the burning rate is not at all dependent on d. This result can be predicted from qualitative considerations ([1]). The value d_{min} is determined from equality of the width of the zone of mixing of component vapors l_{mix} and the width of the vapor-heating zone l_{heat}. From dimensional considerations,

$$l_{\text{heat}} \sim \frac{a_{\text{vap}}}{u_{\text{vap}}} \sim \frac{1}{u}; \qquad l_{\text{mix}} \sim \frac{u_{\text{vap}} d^2}{D_{\text{vap}}} \sim \frac{u d^2}{\rho_{\text{vap}} D_{\text{vap}}}. \qquad (1)$$

For laminar flow,

$$D_{\text{vap}} \sim \frac{1}{p} \sim \frac{1}{\rho_{\text{vap}}}; \qquad l_{\text{mix}} \sim u d^2,$$

therefore the equality $l_{\text{heat}} \sim l_{\text{mix}}$ gives

$$d_{\text{min}} \sim \frac{1}{u}. \tag{2}$$

For turbulent flow,

$$D_{\text{vap}} \sim \nu \text{Re}^{0.8} \sim u_{\text{vap}}^{0.8} d^{0.8},$$

* Relative density $\delta = \rho/\rho_{\text{m}}$ is the ratio of the actual density to the density of a monolith completely free of air inclusions.

to a first approximation, $l_{\text{mix}} \sim d$. From the equality $l_{\text{burn}} \sim l_{\text{mix}}$ we again arrive at (2)*. It follows from this that in Fig. 2 the length of the plateau at $d \leqslant d_{\text{min}}$ should be the shorter, the higher the pressure (i.e., the higher the velocity) to which the given curve corresponds.

For intermediate particle sizes the burning rate begins to decrease noticeably as d increases. Thus, at $p = 10$ atm (Fig. 2), when the particle size is increased from 0.05 to 0.25 mm, the burning rate decreases by a factor of 1.5, i.e., quite substantially.

However, with a further increase in particle size, the dependence $u(d)$ again becomes weaker. This is associated with flame propagation along the contact surfaces of oxidizer grains with the fuel (2). Also significant here is the process of combustion transfer between neighboring oxidizer grains through a bridge of fuel. It may be assumed that if the ratio d/D, where D is the charge diameter, is too large, combustion becomes unstable (at $d/D = 1.7/6 = 0.3$, combustion is still quite stable for $p \geqslant 1$ atm).

Thus, at each given pressure there is a definite interval of particle sizes in which the burning rate changes fairly rapidly with d, while outside this interval it either does not depend on d at all (for $d \leqslant d_{\text{min}}$) or depends on it very weakly (large d). In this case $u_{d \to 0}$ exceeds $u_{d \gg d_{\text{min}}}$ by only a few times. As the pressure is increased, the region of relatively rapid change of burning rate with particle size stretches out and at the same time shifts to the left—into the region of small d.

The complex form of the dependence of burning rate on particle size is apparently connected with the fact that, for different particle sizes, the burning rate is determined by different factors. One may suppose, for example, that at $d \leqslant d_{\text{min}}$ the determining factor is the rate of reactions in the homogeneous vapor mixture; at intermediate d, the rate of mixing of the vapor jets; and at larger d, the rate of flame propagation along the boundaries of the oxidizer particles (2).

As was already noted at the beginning of the article, theoretical studies (1, 3) give a strong dependence of burning rate on particle size. The results of our experiments with mixtures based on $KClO_4$ indicate that this dependence is quite limited. We took into account, however, that in mixtures of $KClO_4$ with bitumen, etc., both components comparatively readily form a gas phase, whereas in works (1, 3) the fuel was assumed to be nonvolatile. Therefore we carried out exploratory experiments with the wood charcoal—KNO_3 system, for which the conclusions of works (1, 3) had been given. Two mixtures were prepared (of identical composition: 15% charcoal and 85% KNO_3). One mixture had fuel and oxidizer particle sizes of $\sim$ 10—20 μ, the other $\sim$ 400μ. At p = 0—50 atm the burning rate of the coarse-grained mixture was only $\sim$ 2 times lower than that of the fine-grained mixture (at p = 50 atm, respectively, $\sim$ 8 and $\sim$ 16 mm/sec), although the particle sizes differed by tens of times.

Thus, the conclusions of works (1, 3) do not describe the experimental data, including for the very system (black powder) that was specially considered in (1). Apparently, for the most widespread mixed systems the theoretical model of combustion must be substantially modified in comparison with work (1), possibly taking into account the considerations expressed in the present note.

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* In the coordinates (u, p), the presence of $d_{\text{min}} \sim 1/u \sim 1/p^n$ leads to the result that the family of curves $u(p, d)$, where d is a parameter, must have an envelope (which corresponds to $d \to 0$), and each given curve $u(p, d_i)$, to the left of the point of contact with the envelope, merges with it. In other words, the family $u(p, d)$ must have the form of a palm branch. In Fig. 1 the curves corresponding to particle sizes 0.01 and 0.07 mm touch each other at $p = 1$ atm ($u = 1$ mm/sec). This means that at $u = 1$ mm/sec, $d_{\text{min}} \sim 0.07$ mm.

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

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