PECULIARITIES OF EROSIVE COMBUSTION OF HETEROGENEOUS SYSTEMS

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Abstract

Different options of the combustion models are analyzed and estimations are made for the effect of high velocity combustion gases flow parallel to the burning surface. For EM with the burning rate control condensed phase reactions the new explanation of the negative erosion effect is suggested. For EM based on the mono disperse coarse RDX exhibiting "drop" in the burning rate pressure dependence it is expected the shift of the "drop" towards the higher pressures. For the pressed mixtures of coarse-grain AP with the polystyrene, having a maximum in dependence of the burning rate on AP particle size, it is expected shifting the maximum in direction of the large particle size. For EM with fast-burning binder the non-stationary erosive effects are proposed (for example, under tangential oscillations of the combustion products flow in the burning charge bore) even if in a stationary regime the burning rate does not depend on tangent gas flow. For EM containing the low melting temperature fillers the effect of removal of the melt layer from the burning surface is discussed.

Introduction

So-called erosive burning of energetic materials (EM) occurs when the EM burning surface is subjected to a high-velocity combustion products flow parallel to it. Erosive burning of homogeneous EM with the gas phase burning rate control reactions has been theoretically analyzed by Vilyunov [1] who proposed rather simple expression for calculation of the burning rate in dependence on the ratio of the mass flow rates for the gas streams in tangent and normal directions regarding the burning surface. Mathematical modeling the gas flow behavior with the gas blowing in normal direction has been carried out successfully [2, 3]. More difficult problems arise in the combustion modeling of the EM burning with tangent high-velocity gas flow.

In [4], a simple approach for solving that problem is demonstrated: in the combustion model without tangent gas flow (petite ensemble model) the gas phase transport factors are taken in the form, which accounts their enhancement due to effect of turbulence. Approximately, the turbulence is considered for the case of inert body slipping with the given velocity gas.

The goal of the present work is to pay attention to possible options of particular combustion models with account of the effect of high-velocity gas flow. There is not possibility to construct universal description of the erosive combustion for different type EMs and different gas flow regimes. We will follow the M.A. Lavrentjev common approach (see introduction to [5]), which implies analysis of particular situations for the complex phenomena followed by its generalization after accumulation of sufficient volume of information.

Analysis of particular approaches.

Let's consider expected erosive effects for several combustion models. We will have deal with the models for homogeneous EM with evaporation on a surface, for pressed samples of neat coarse RDX and mixture of coarse AP with the polystyrene, as well as for EM with fast-burning binder.

1. For the combustion model of homogeneous EM with the surface evaporation and with the condensed phase burning rate control reactions it is necessary to take into account the "intrinsic" (inherent) turbulence, which generates instability of the processes in the reaction zone of the condensed phase [6, 7]. This results in self-sustaining oscillations of the rate of subsurface reactions. Such oscillations are not described by the Zeldovich - Novozhilov phenomenological theory, which assumes the subsurface reaction zone being quasi-stationary.

Corresponding increase in the magnitude of the gas transport factors (and relevant enhancement of the heat feedback from the gas to the burning surface) can be estimated in semi-quantitative manner. Let a zero-order reaction proceeds in a liquid layer with the rate $\rho_c \partial\varepsilon/\partial t = W(T)$. Here ρ_c is the density; ε is the extent of decomposition. In the regime with the condensed phase burning rate control role the oscillations of the burning rate arise with a characteristic time $t_{osc} = \rho_c / W(T_s)$. These oscillations are not necessary synchronous over the burning surface; it is natural to consider them disordered in a phase. The disordered oscillations of the gas blowing represent the near surface turbulence with a mixing factor $D_{eff} = \mathrm{const}$

$(\Delta v_g)t_{osc}$. Here Δv_g is the fluctuation of the gas blowing velocity having the magnitude close to that of the mean gas blowing speed (with developed oscillations the speed magnitude changes from zero to maximum). Note that on the burning surface a tangent gas velocity is equal to zero and the turbulence near the surface is non-isotropic.

As is known, in nonlinear systems self-organization of random processes is possible and, as a rule, is realized. In particular, the mentioned above reaction rate oscillations can manifest themselves as the intermittent hot spots or cross-running waves across the burning surface. It was stated in [8] that oscillations of such type were observed in a wide range of pressures for numerous EM, even if they burn in the stability domain according to the Zeldovich – Novozhilov theory. The "permanent" turbulence generated in the combustion of heterogeneous propellants was discussed earlier in [9, 10], but the oscillations there were born by the perturbations of a gas flowing out of the burning surface caused by inhomogeneity of original EM.

One may suppose that parallel to the burning surface gas flow will destroy the structure of the combustion-born turbulence and, consequently, the contribution due to turbulence into the heat feedback to the surface will decrease. Actually, the combustion-born non-isotropic turbulence has the finite linear scale of the order of magnitude equal to $\sim\rho_c\Delta v_g / W(T_s)$. At the same time, created by the tangent gas flow turbulence is close to isotropic type with pulsations amplitude diminishing in value when approaching the burning surface. Thus, it is possible to consider that near to the surface the large-scale normal pulsations will be blurred by small-scale tangent pulsations. The higher the tangent gas velocity, the larger effect of diminishing the contribution of the intrinsic turbulence into the gas heat feedback to the burning surface. On the contrary, the contribution of the external gas flow turbulence into the gas heat feedback becomes larger with the gas velocity. It is easy to recognize (figure 1) that with increase in the tangent gas velocity the total heat flux to the surface (and, as a consequence, the burning rate) passes through a minimum. Thus, the concept of existence of "intrinsic" turbulence close to the surface allows suggesting novel mechanism of so-called negative erosion. It can take place in combustion of homogeneous EM with the burning rate control reactions in the condensed phase, as well as in combustion of fuel rich composite propellant containing the coarse heterogeneous filler capable of independent burning.

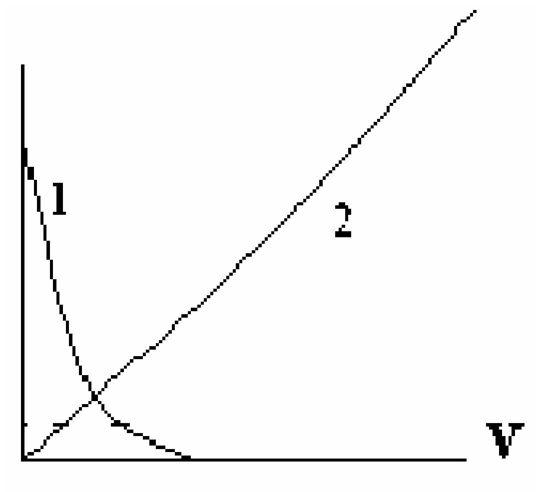

Figure 1. Qualitative diagram for the value of heat fluxes to the burning surface in dependence on the tangent gas flow velocity. 1- due to “intrinsic” (combustion-born) turbulence; 2 - due to tangent gas flow.

2. When modeling the combustion of fuel rich composite propellant containing coarse heterogeneous oxidizer capable of independent burning it is necessary to take into account similar to the above mentioned "threshold" effect. In [11], it is reported that in combustion of formulation based on RDX with large enough particle size the burning rate demonstrates negative jump when pressure decreases (for RDX of smaller size the "jump" from vertical becomes inclined). As an explanation of this fact it was proposed [11] to consider the effect of relatively low melting point of RDX. According to [11], the combustion wave propagates either in a layer by layer manner if the RDX particles are totally melted in the reaction zone or in a convective burning mode with enhanced burning rate if they are melted only partially. Earlier such phenomenon was observed in combustion of the samples of pressed RDX when convective burning resulted in onset of detonation regime. However, in the experiments [11] the "convective" burning rate practically coincided with the burning rate for neat RDX. It is shown in [12,13] that most plausibly “the burning rate drop” effect [11] can be explained by disappearance (diffusion blurring) of hot own RDX flame at fulfillment of

the condition $\rho D/md > f(\alpha)$, which occurs when pressure decreases. Here ρ is the density of gas, D is the diffusion coefficient (value of ρD practically does not depend on pressure), m is the mass burning rate (positively depending on pressure), d is the size of RDX particles, $f(\alpha)$ is some function depended on excess of oxidizing agent (for stoichiometric mixture α=1, in compositions on the basis of RDX $\alpha \ll 1$).

The analogous effect takes place [14] in the case of combustion of AP/polysterene mixtures (see figure 2b). More correctly: disappearance of the hot diffusion flame when condition $\rho D/md > f(\alpha)$ is hold can plausibly explain the presence on a curve of m (d) a section with positive dependence, at first sight difficultly explained. Such section is absent at $\alpha = 1$, but it appears and becomes more expressed with α decreasing. In fact, for a section with negative dependence it is easy to assume the "relay-race" mechanism of the combustion wave propagation from one diffusion flame site to another. Such mechanism (especially when taking account of dependence of ignition time on the filler particle size) gives negative dependence for m (d). However, at sufficient decrease in d the hot spots disappear, and the burning rate should decrease sharply (the more strongly, the higher the deficiency of oxidizing agent 1 - α). This results in appearance of section with the positive m(d) dependence. In this case real non-unimodal particle size distribution of filler in the combustible material provides an inclined section instead of sharp drop in m-d coordinates.

Superposition of a parallel to the surface gas flow increases effective value of D that promotes destruction and disappearance of the local flames. Therefore, one may expect for conditions of experiment [11] (figure 2a) "the burning rate jump" shift towards the area of higher pressures; and for conditions of experiment [14] (figure 2b) - moving a section of positive dependence m (d) towards the area of larger particle sizes. In other words: the criterion of disappearance of the flame spot $\rho D/m(p)\, d = f(\alpha)$ with increase in D (due to gas tangent flow) will be reached for figure 2a at the greater (if compared with no gas tangent flow conditions) values of P, and for figure 2b at the greater values of d (to match equality $\rho D/m(p)\, d = f(\alpha)$ the increase in numerator has to be compensated by increase in denominator). The burning rate decrease represented on some sections in figure 2 can be apparently treated as a sort of negative erosion effect.

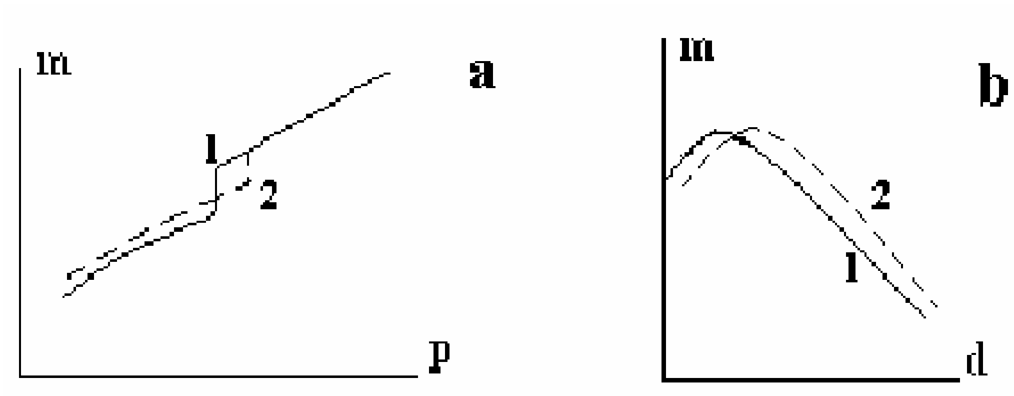

Figure 2. **a** - burning law for the propellant based on the coarse-grain RDX. Solid line 1 - the experimental data [11] without tangent gas flow, dotted line 2 – the expected burning law with tangent gas flow; **b** - burning law for the propellant based on a coarse-grain AP and polysterene. Solid line 1 - the experimental data [14] without tangent gas flow, dotted line 2 - the expected burning law with tangent gas flow.

3. In combustion of the propellant with energetic binder which burns faster of oxidizer, the burning rate control zone is hidden in narrow layers of binder between the oxidizer coarse grains. They protect the burning rate control zone from the action of tangent gas flow. Therefore at a stationary flowing regime for such composition it is possible to expect weak or zero erosive burning effect. The “uniform“ erosive burning theory predicts an absence of erosive burning effect for such compositions under non-stationary tangent gas flow [15]. On the contrary, it is theoretically shown in [16] that in combustion of propellant with fast-burning binder the erosive burning effect can occur in the presence of non-stationary tangent gas flow even if it does not exist in the presence of stationary tangent gas flow. The reason for that is that the form of grains of filler protruding over a burning surface can depend on intensity of tangent gas flow: the higher the gas flow velocity, the smaller protruding edges. Variation of

the tangent gas flow velocity leads to variation of the total mass of the edges. This produces the non-stationary additive to mass burning rate.

Below we reproduce the result of [16]. Let the fast-burning component burns with a constant rate u_{st} (not dependent on the gas tangent flow velocity v), and the edge height h of a slow-burning component depends in a stationary tangent gas flow regime on the gas tangent flow velocity by the law $h_{st}(v)= h_0 - kv^2$ while in a non-stationary regime $dh/dt = -A\,[h-h_{st}(v(t))]$. Then, in the combustion under oscillations of the gas tangent flow velocity $v = v_a \cos(\omega t)$ and at the elementary assumption about the triangular form of the edges the magnitude of the ratio R(t) of mass flow rates for slow and fast burning components is calculated by

$$\frac{\mathrm{R(t)}}{\mathrm{R_{st}}} = 1 - \frac{kv_a^2}{2u_{st}} \frac{\omega}{\sqrt{1+(2\omega/A)^2}} \sin(2\omega t - \varphi), \quad \varphi = arctg(2\omega/A)$$

If mixed above the burning surface the gasification products of slow and fast burning components react readily in the gas flame, the maximum gas temperature is unambiguously determined by the ratio of the mass flow rates for the components. Thus, the oscillations of the flame temperature can be estimated on the basis of above expression. Reversal oscillations of the gas tangent flow velocity are implemented, for example, at tangential combustion instability (caused by the pressure oscillations) in the bore of cylindrical EM charge.

4. For compositions with easily melted components it is possible to expect intense ablation of the melted surface layer by a gas stream. Experimental studies on the effect of a tangent gas flow on the burning rate were carried out in the past mainly for double base and for composite propellants based on AP and inert polymer binder. It was shown that tangent gas flow affects burning rate via modification of the thermal conductivity mechanism: originated due to tangent gas flow turbulence enhances a heat feedback to the surface of EM. “Real erosion” effects or mechanical interaction was manifested only as the surface waves observable on the recovered samples. The reason for that can be protecting action of the carbonaceous carcass formed in the

nitrocellulose decomposition and a very small thickness of the melted layer on AP burning surface.

The situation can be changed with use of formulations based on low melting point oxidizers like HMX (T_m = 280°C), RDX (T_m = 204°C), HNF (T_m = 124°C), ADN, CL-20. The presence of high velocity tangent gas flow may lead to removal of melted material from the burning EM surface with its subsequent disintegration and delayed burning of drops. In turn, it leads to diminishing the heat losses on evaporation and apparent increase in the burning rate. Thus, the “truly erosive” burning can be observed for the EM with thick melted layer. Indirect evidence of such a mechanism can be found in experiments [17] where the PETN particles burned behind the detonation front with the rate by an order of magnitude higher than that in conditions of zero gas flow velocity at the same pressure. In the opposite case, if the filler (oxidizer) has relatively high melting point and the binder is easy melting the filler grains entrainment can occur with an apparent effect of erosive burning.

Conclusion

The above considerations testify to variety of the erosive burning modes. The paper gave few particular examples of the combustion behavior of EMs under tangent gas flow interaction with the burning surface. Some of the examples look obvious, like opportunity of a removal of melted layer by the tangent gas flow, another options take special consideration and experimental verification. It regards to the plausible explanation of the negative erosion effect and existence of erosive burning in unsteady gas flowing conditions for the propellants which have very weak dependence of the burning rate on stationary tangent gas flow velocity.

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