Condensed Combustion Products of Aluminized Propellants. II. Evolution of Particles with Distance from the Burning Surface

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Condensed combustion products of a model propellant on the basis of ammonium perchlorate and aluminum were studied using the sampling technique. The granulometric composition of combustion products and the content of metal aluminum in particles of size from 1.2 μm to maximum were determined within the pressure range of 0.6-7.5 MPa at a distance from the burning surface up to 190 mm. A multimode structure of mass distributions of oxide particles within the size range of 1.2-40 μm was found. An empirical dependence of burnout of metal aluminum from agglomerates on the residence time of particles in the plume of combustion products of the propellant sample was obtained.

INTRODUCTION

The advisability and effectiveness of using aluminum as part of a solid propellant for a rocket motor are determined not only by the heat release during aluminum combustion but also by the characteristics of condensed combustion products (CCP) formed in this process. Damping of gas oscillations in the combustion chamber, two-phase losses of the specific impulse, deposition of slag in the motor, erosion of the nozzle block, optical characteristics of the plume, ecological consequences of operation of the rocket motor - this list of the processes and phenomena somehow associated with CCP characteristics is far from being complete. Mathematical simulation of these processes requires experimental information on the granulometric and chemical composition of the CCP. Obtaining this information is the main objective of the present work.

The tendency of aluminum to agglomeration leads to the fact that a two-phase flow of propellant-combustion products in the general case contains agglomerates whose size is considerably greater than the size of the initial aluminum particles in the propellant, nonagglomerated particles whose size is close to the initial one, and oxide particles whose size varies from tenths to tens of micrometers [1,3] depending on the mechanism of their formation. It has been found experimentally that the size distribution of the mass of condensed combustion products for most aluminized propellants has a multimode form shown schematically in Fig. 1. The “global” mode No. 1 within the range \( D = 0.3 \, \text{to} \, 2 \, \mu m \) is usually associated with condensation of oxide vapors on nucleation centers in the plume (vapor-phase mechanism) [4]. The

![Fig. 1. Qualitative character of the size distribution of condensed combustion products of aluminized propellants.](image-url)
TEST CONDITIONS

The present paper describes the results of a gravimetric and chemical analysis of condensed combustion products of a model composite propellant containing ammonium perchlorate (AP), energy binder, and 23.4% of aluminum. According to the classification of [5], this propellant refers to condensed systems of class A whose characteristic feature is the subsurface heterogeneous combustion of aluminum (in the flame layer). The experiments were performed using the technique of [21]. Propellant samples of diameter of 6 mm and height of ≈7 mm were burned in nitrogen at pressures p = 0.6, 2.0, 4.0, and 7.5 MPa. The nitrogen flow rate was 1.4 g/sec in experiments with p = 0.6 MPa and 3.4 g/sec in the rest of the cases. For each value of pressure, the length of the protective tube was varied (L_t = 0, 10, 86, and 190 mm) to obtain data on CCP evolution with distance from the burning surface. Propellant samples were tightly fixed in Plexiglass glasses, which played the role of burning inhibitor. In experiments without the protective tube (L_t = 0), the propellant sample prior to burning was flash-mounted with the glass walls. The internal diameter of the glasses, the internal diameter of the protective tube, and the sample diameter were identical.

TRANSFORMATION OF THE MASS DISTRIBUTION OF CCP PARTICLES UNDER VARIED BURNING CONDITIONS

Figure 2 shows the mass distributions of CCP particles within the size range from 1.2 μm to maximum, which were obtained under the most favorable and adverse test conditions from the viewpoint of aluminum burnout: the results of experiments without the protective tube at low pressure and with the maximum length of the protective tube at high pressure are plotted in Fig. 2a and b, respectively. The values of the incompleteness of aluminum combustion η defined as the ratio of the mass of aluminum in sampled particles to the mass of aluminum in the propellant are 0.05 and 0.15, respectively. The ordinate axis shows the quantity f defined as the quotient of the CCP mass within a certain range of sizes and the range width and propellant mass, i.e., the size distribution density of the relative CCP mass. If the abscissa axis has a linear scale, the area under the histogram is proportional to the mass of particles within a given range of their size [21].

“global” mode No. 2 within the range D = 4.8 μm is related to oxide condensation on the surface of a burning aluminum-containing particle and to coagulation of oxide particles in the vicinity of the burning particle. CCP particles with D > 30 100 μm (global “mode” No. 3) are assumed to be agglomerates consisting mainly of aluminum and aluminum oxide; the term “mode” here is rather conventional, since the size distribution of agglomerates has a multimode nature [5]. Under certain conditions (special features of the propellant composition or a sufficiently long residence time of agglomerates in the plume), the so-called “coarse” oxide particles are formed as a result of complete burnout of aluminum from agglomerates. The usual size of these particles is tens of micrometers; therefore, they also belong to mode No. 3 [9].

In addition, a significant amount of nonreacted aluminum can be found for propellants with weakly expressed agglomeration in mode No. 2 [7].

As is seen from the review in [8], most papers dealing with CCP characteristics employ contact methods, which allow one to sample and analyze either oxide particles (mode Nos. 1 and 2) [9, 10] or agglomerates (mode No. 3) [11–15]. At the same time, it is obvious that the study of CCP evolution that occurs with increasing distance between the particles and the burning surface of the propellant should include both the variation in the mass, size, and chemical composition of agglomerates and the dynamics of mass distribution of oxide particles formed in the course of aluminum burnout from agglomerates. Therefore, it is necessary to determine CCP characteristics within the entire range of sizes. This problem is solved using techniques that sample and analyze the entire mass of condensed products formed during combustion of a small propellant sample [6, 16–20]. This idea (collection of all CCP particles) formed the basis of the technique of [21] applied in the present work. The facility of [21] has no major constraints on the size of the sampled particles. However, the actual range of particles analyzed was from 1.2 μm to maximum, which was conditioned by the use of a “Malvern-3600E” granulometer for granulometric analysis of small particles. In other words, we study fragments of “total” distributions of the CCP, including particles of the global mode Nos. 2 and 3 (see Fig. 1). According to the estimate of [21], for typical propellants, the mass fraction of particles with D < 1.2 μm outside of the range considered does not exceed 5% of the overall CCP mass, and their absence has practically no effect on the type and characteristics of the mass distribution of particles within the size range under consideration.

Condensed Combustion Products of Aluminized Propellants. II