The possibility of reducing the content of aerosol particles in the products of solid propellant combustion

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The possibility of reducing the content of aerosol particles in products of combustion of metal-free propellant systems by partially replacing the ammonium perchlorate with the ammonium nitrate is considered.

Introduction

In the modern compositions of metallized and metal-free solid propellants (SPs), ammonium perchlorate (AP) is used as oxidants. The products of SP combustion contain toxic components (in particular, hydrochloric acid) and aerosol particles.[1,2]

In connection with the increasing environmental requirements, it is an urgent problem to seek nontraditional alternative approaches, making the space rocket objects more friendly to the environment.

One of the promising ways in solving this problem is the use of ammonium nitrate (AN), as a partial or full substitute for the AP. The aim of this work was to determine experimentally the content of condensed matter in SP combustion products, containing AP and AN in different percentage.

Experimental technique

The experiments were conducted in a constant-pressure device having a volume of 2.4 liter and equipped with a specialized quartz sampler (volume of 0.5 liter, mass of 25 g) and a valve for regulated valve pressure dumping, which allows the slow pressure dumping and provides for the complete sampling of the condensed phase of the combustion products. The experimental system is schematically shown in Fig. 1. The experimental technology is as follows:

1. The mass of a sample m_1 is measured.
2. A sample is placed on a textolite substrate, and an igniter is connected.
3. The mass of the dried sampler m_2 is measured, and the sample under study is covered with the sampler.
4. The constant-pressure device is assembled and filled with nitrogen to a preset pressure.
5. The igniter is turned on, and the studied sample is burned out. During the experiment, the pressure in the device does not increase, because it is connected to a receiver (omitted in Fig. 1).
6. Once the burning terminates, gaseous combustion products are slowly let out, the device is disassembled, the sampler is taken out, and the condensed combustion products are collected from the textolite substrate and placed in the sampler.
7. The sampler is dried at a temperature of 70–75°C and its mass m_3 is measured.
8. The content of the condensed substances in the combustion products is determined as

$$Z = \frac{m_3 - m_2}{m_1} \cdot 100, \text{ mass \%}.$$

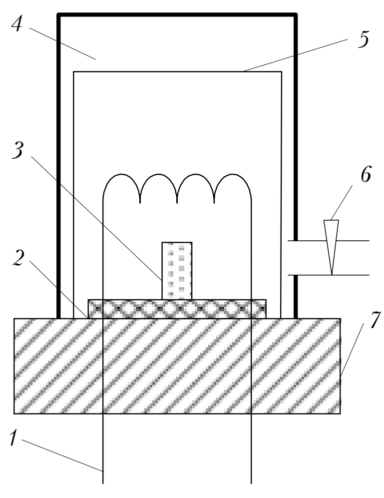

Fig. 1. Device for sampling of condensed combustion products: nichrome wire igniter *1*, textolite substrate *2*, propellant sample *3*, constant-pressure device *4*, quartz sampler *5*, valve *6*, head of the constant-pressure device *7*.

The error of the mass measurements was 0.002 g. The relative error of Z determination within the 0.95 confidence interval did not exceed 10%.

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In the experiments, cylindrical SP samples 10 mm in diameter, 35–40 mm in height, and 10 g in mass, produced by the through-feed press method, were used. The systems containing AP and the mixed AP + AN oxidant were investigated. The size of AP particles is smaller than 50 μm, and the size of AN particles is smaller than 100 μm. The oxidant excess factor of the considered systems varied in the range α = 0.40–0.52, which is typical of regular SP compositions. Thermostable butyl rubber was used as a fuel-binder.

Results

The results of experimental investigations carried out at a pressure of 2 and 6 MPa, characteristic of the real conditions of SP combustion in an engine, are given in Tables 1–3 and in Figs. 2 and 3.

The effect from the inclusion of AN into the oxidant is demonstrated in Table 1 and in Fig. 2.

Table 1. Content of condensed substances in combustion products (α = 0.43)

Oxidant composition, mass %		*Z*, mass %	
AP	AN	*p* = 2 MPa	*p* = 6 MPa
100	0	9.4	7.3
99	1	7.9	6.5
98	2	6.6	6.0
96	4	5.6	1.5
94	6	5.5	1.5
92	8	5.6	1.5
90	10	5.2	1.0
85	15	6.1	1.6
80	20	7.2	1.4
75	25	7.0	6.0
70	30	7.5	6.1
60	40	–	6.1
50	50	–	–

Table 2. Content of condensed substances in combustion products (90% AP + 10% AN)

Oxidant composition, mass %	α	*Z*, mass %	
		p = 2 MPa	*p* = 6 MPa
70.0	0.40	12.8	8.2
75.0	0.43	5.2	1.0
79.0	0.46	4.7	1.0
82.0	0.52	3.2	0.8

Table 3. Composition of condensed combustion products (α = 0.43)

Oxidant composition, mass %		*Z*, mass %		Composition of condensed combustion products, mass %			
				p = 2 MPa		*p* = 6 MPa	
AP	AN	*p* = 2 MPa	*p* = 6 MPa	soot	NH_4Cl	soot	NH_4Cl
100	0	9.4	7.3	57.0	43.0	46.0	54.0
96	4	5.6	1.5	40.0	60.0	30.0	70.0

The introduction of 4–10 mass % of AN into the oxidant leads to a 70% reduction in the content of condensed substances in combustion products at 2 MPa and to the 4.9 times reduction at 6 MPa. Addition of 4 mass % AN to the oxidant, favors a serious reduction of the content of condensed combustion products. Their amount remains nearly constant, if 4–10 mass % AN is added.

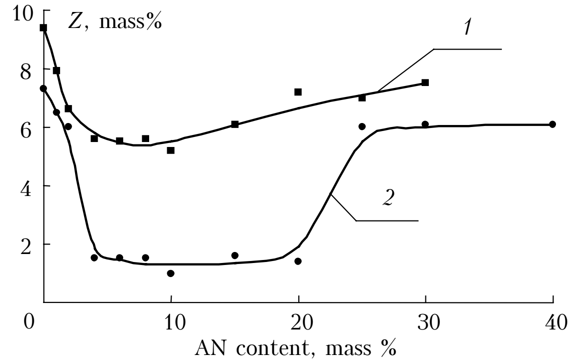

Fig. 2. Content of condensed substances in combustion products at α = 0.43 as a function of the AN content: *p* = 2 MPa (*1*); *p* = 6 MPa (*2*).

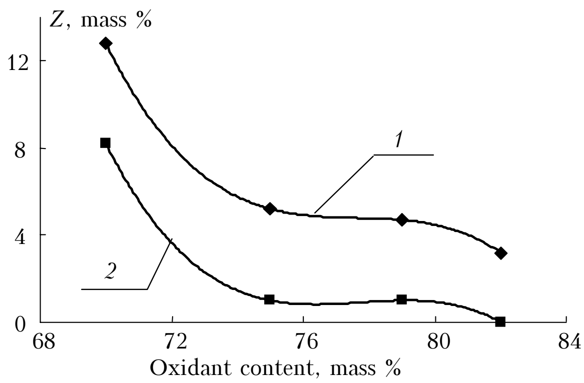

Fig. 3. Content of condensed combustion products as a function of the oxidant content in the propellant (90% AP + 10% AN): *p* = 2 MPa (*1*); *p* = 6 MPa (*2*).

If more than 10 mass % AN is added to the oxidant, the amount of condensed combustion products increases again. This result can be explained by the fact that upon the AN decomposition, nitrogen oxides are formed, which in small amounts serve as catalysts of SP decomposition and burning. If the content of AN in the oxidant increases and, correspondingly, the amount of produced nitrogen oxides increases, then, according to the results obtained, we can assume the reduction of their catalytic ability. It should be noted that the increase of the AN content in the oxidant in excess of 10% at a fixed α leads to incomplete combustion of the propellant and, as a consequence, to the increase of the condensed substances in the combustion products. At a pressure of 6 MPa, the described effect becomes more pronounced, which can be explained by a more complete, than at 2 MPa, reaction, because the temperature and the rate of combustion increase as the pressure increases. Systems, containing only AN, do not burn at this α.

The data on the content of condensed substances in SP combustion products for different oxidant content in the propellant and for different oxidant excess factor α are presented in Table 2 and Fig. 3.

The increase of the oxidant excess factor of the propellant leads to the reduction of the content of condensed substances in combustion products, all other conditions being the same. As the oxidant content increases (75.0– 82.0 mass %), the amount of condensed products decreases insufficiently. This result can be explained by the catalytic activity of nitrogen oxides.

The results of the analysis of condensed SP combustion products are tabulated in Table 3.

The analysis of the chemical composition of condensed combustion products was carried out by use of a standard technique. The results of the analysis have shown that the main components of condensed combustion products are soot and ammonium chloride NH_4Cl. The amount of condensed combustion products produced at a pressure of 6 MPa is smaller than at 2 MPa.

With the increase of the pressure, the combustion temperature rises, and, consequently, the reaction rate increases, as well as the amount of gaseous SP combustion products. On the contrary, the amount of NH_4Cl for 6 MPa increases as compared to the reaction proceeding at 2 MPa, since the increased pressure favors the production of NH_4Cl.

The data on the composition of chlorine-containing gaseous substances in SP combustion products for different oxidant composition are summarized in Table 4, which presents the percentage of gaseous substances in the total amount of combustion products.

Table 4. Composition of chlorine-containing gaseous combustion products (p = 2 MPa)

Substance	Content of chlorine-containing substances, mass %	
	AP	90% AP + 10% AN
HCl	29.860	26.360
Cl_2	0.920	0.180
ClO	0.005	0.002
HClO	0.030	0.020
Total	30.815	26.562

The partial substitution of AP with AN along with the reduction of the content of condensed combustion products leads to a decrease in the content of chlorine-containing substances in combustion products, which is confirmed by the data of thermodynamic calculation of the equilibrium composition of combustion products by the technique from Ref. 3. The SP combustion products contain a significant amount of chlorine-containing substances such as hydrochloric acid HCl, molecular chlorine Cl_2, chlorine oxide (II) ClO, and hypochlorous acid HClO.

Conclusions

The results of the experimental investigations carried out in this work suggest the following:

• The combustion products of metal-free solid propellants based on AP and butyl rubber contain a significant amount (up to ~ 10 mass %) of condensed substances, consisting of aerosol particles of soot and ammonium chloride, as well as chlorine-containing gaseous components.

• The addition of 4–10 mass % of AN, partly substituting AP, to the oxidant leads to the reduction of the content of condensed substances in combustion products (by 70% at a pressure of 2 MPa and 4.9 times at 6 MPa).

• The increase of the oxidant excess factor of the propellant composition in the range α = 0.40–0.52, all other conditions being the same, also leads to reduction of the content of condensed substances in SP combustion products (4 times at 2 MPa and 10.3 times at 6 MPa).

• The effect of reduction in the content of condensed substances in combustion products becomes more pronounced as the pressure in the combustion chamber increases from 2 to 6 MPa. This is caused by a more complete combustion, higher combustion temperature, and higher rate of chemical reactions at higher pressures.

• The addition of 10 mass % ammonium nitrate, partly substituting ammonium perchlorate, to the oxidant leads to the 13.8% reduction of chlorine-containing gaseous combustion products (at a pressure of 2 MPa).

• Thus, as a small amount (up to 10 mass %) AN, partly substituting for AP, is added to a propellant, containing AP as an oxidant, the content of condensed and chlorine-containing gaseous components in combustion products decreases significantly, which mitigates the effect of the space-rocket activity on the environment.

Acknowledgments

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