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THERMODYNAMIC CALCULATIONS FOR DETERMINING THE TEMPERATURE OF COMBUSTION PRODUCTS OF PYROTECHNIC PRODUCTS BASED ON ALUMINUM-MAGNESIUM ALLOY POWDER

This article is devoted to the study of the fire-hazardous properties of pyrotechnic products based on powders of aluminum-magnesium alloys with a nitrate-containing oxidizer ($NaNO_3$). The article presents thermodynamic calculations of temperature and composition of combustion products of these products depending on the ratio of components and the state of the environment. The obtained results make it possible to determine possible fire-hazardous situations at the stage of development and design of pyrotechnic products based on them. Such information helps prevent possible fires and accidents when storing and launching pyrotechnic products.

Key words: *pyrotechnics, igniters, combustion, agglomerates, thermodynamic calculations, fire safety, warehouses.*

Formulation of the problem. Calculation of thermodynamic parameters of pyrotechnic mixtures with heterogeneous and homogeneous combustion products is a difficult task. For this, it is necessary to perform thermodynamic calculations based on the solution of a system of nonlinear algebraic equations, such as chemical equilibrium, material and energy balance. Calculations are made under a number of assumptions, including infinitely large rates of chemical reactions, perfect mixing of components, no heat transfer, uniformity of temperature and pressure fields, and equilibrium distribution of energy over degrees of freedom.

For heterogeneous products, assumptions of phase, thermal and dynamic equilibrium of the condensed substance are additionally introduced, the volume of which is usually neglected. Calculations are made for different types of pyrotechnic products, including considered pyrotechnic igniters with homogeneous and heterogeneous combustion products. As a result of calculations, the composition of combustion products and their thermodynamic parameters are determined.

Therefore, carrying out thermodynamic calculations of the temperature and composition of the combustion products of mixtures will allow to more accurately establish the influence of technological factors on the rate of development of the combustion process of mixtures, thereby preventing the unstable and explosive development of the combustion process.

Analysis of recent research and publications. In various scientific works [3, 4] a method of calculating the combustion products of highly metalized pyrotechnic mixtures containing more than 30-40% of metal fuel is proposed. This method is based on the fact that initially, by means of free energy minimization, the phase state of all reaction products and their approximate concentrations are determined. Then, with the help of a modified method of equilibrium constants, the exact values of the concentrations of the reaction products and the

equilibrium temperature are found. This approach makes it possible to obtain information on the thermodynamic properties of approximately 740 gaseous and 250 condensed compounds that make up 47 chemical elements in dialog mode and in real time on modern computers using standard application program packages. This method makes it possible to more accurately determine the influence of technological factors on the rate of development of the combustion process of mixtures and prevent its unstable and explosive development [5, 6, 7].

As it is known, the assessment of the energy potential of mixtures can be carried out by the specific impulse [2]:

$$I=(\frac{2k}{k-1}\cdot\frac{R_0}{\mu g}T_к\eta_t)^{\frac{1}{2}}, \quad (1)$$

where k – adiabatic exponent; g – acceleration of gravity; R_0 – gas constant; $T_к$ – temperature in the combustion chamber; μ – molecular weight of combustion products; $\eta_t=1-(\frac{P_0}{P_к})^{\frac{k-1}{k}}$ – thermal efficiency of the engine; $\frac{P_0}{P_к}$ – the ratio of pressures at the outlet and in the combustion chamber.

Setting the problem and solving it. Thermodynamic calculations of the dependences of the temperature and the composition of the products of combustion of pyrotechnic products on the coefficient of oxidant excess, external pressure and the nature of the oxidant can be useful for understanding and optimizing the combustion process.

For example, an increase in the oxidant excess ratio can lead to an increase in temperature and a change in the composition of combustion products. A change in external pressure can also affect the temperature and composition of combustion products, especially in the case of heterogeneous systems. The nature of the oxidizer can also affect the thermodynamic properties of the combustion process and the composition of the combustion products.

Taking these factors into account can help in optimizing the composition of pyrotechnic products and increasing their effectiveness.

Presentation of the main research material. Indeed, to achieve a higher specific impulse, it is necessary to use pyrotechnic compositions with combustion products that have a high combustion temperature and increased heat content. To achieve this, you can use various metal fuels such as magnesium, aluminum, titanium, beryllium, zirconium, etc which have a high heat content and a high combustion temperature.

You can also use special oxidizers that have a high burning temperature and provide energy synergy with metal fuels. For example, ammonium and potassium nitrates, potassium perchlorate and others. It is also important to ensure the correct ratio between the metal fuel and oxidizer, as well as good mixing of the components to obtain a homogeneous mixture.

However, when developing new pyrotechnic compositions, it is necessary to take into account not only their thermodynamic properties, but also other factors, such as safety of production and operation, resistance to moisture, stability during transportation and storage, interaction with other materials, etc.

To determine the optimal composition of the pyrotechnic mixture, it is necessary to analyze the data of thermodynamic calculations of the temperature of the combustion products and their relative content of high-temperature condensate for various stoichiometric mixtures of metal fuels and oxygen-containing oxidizers. The data of this table 1 can be used to select the composition of the mixture with the desired combustion temperature and heat content.

To increase the specific impulse of the mixture, it is necessary to look for such compositions, the combustion products of which have an increased heat content and a high combustion temperature. For example, it can be seen from the table that compositions containing barium and aluminum have a high combustion temperature and increased heat content compared to other compositions.

However, it is worth noting that when choosing the composition of the mixture, it is necessary to take into account not only thermodynamic characteristics, but also other factors, such as safety, stability and the possibility of mass production [1].

Table 1 – The main thermodynamic characteristics of stoichiometric two-component pyrotechnic mixtures of metal fuel + oxygen-containing oxidizer

Mixture Charac-teristic	*P*, MPa	Mg + $NaNO_3$	Mg + KNO_3	Mg + Ba $(NO_3)_2$	Mg + Sr$(NO_3)_2$	Al + $NaNO_3$	Al + KNO_3	Al + Ba $(NO_3)_2$	AMC + $NaNO_3$
$T_г$, K	10	3988	3966	4188	4154	4714	4670	4737	4350
	1,0	3090	3089	3098	3143	3743	3738	3768	3417
	0,1	2533	2533	2547	2570	3042	3040	3062	2789
$g_к$	10	0,64	0,58	0,68	0,72	0,66	0,59	0,50	0,65
	1,0	0,48	0,44	0,36	0,62	0,61	0,54	0,39	0,53
	0,1	0,46	0,41	0,30	0,51	0,58	0,52	0,38	0,41
Mixture Charac-teristic	*P*, MPa	AMC + KNO_3	AMC + $Ba(NO_3)_2$	AMC + $Sr(NO_3)_2$	Mg + NH_4NO_3	Mg + $RbNO_3$	Mg + NH_4ClO_4	Mg + $KClO_4$	Al + NH_4NO_3
$T_г$, K	10	4318	4528	4463	3627	3982	3930	4250	4130
	1,0	3415	3471	3433	2941	3091	3039	3155	3409
	0,1	2787	2823	2805	2443	2533	2500	2668	2819
$g_к$	10	0,59	0,69	0,57	0,59	0,46	0,41	0,41	0,67
	1,0	0,48	0,56	0,38	0,43	0,35	0,29	0,33	0,65
	0,1	0,45	0,51	0,34	0,38	0,33	0,28	0,28	0,67
Mixture Charac-teristic	*P*, MPa	Al + $RbNO_3$	Al + NH_4ClO_4	Al + $KClO_4$	Be + NH_4NO_3	Be + $NaNO_3$	Be + KNO_3	Be + Sr $(NO_3)_2$	Be + Ba $(NO_3)_2$
$T_г$, K	10	4691	4537	5071	3726	4746	4692	4862	4607
	1,0	3742	3581	3839	3102	3792	3786	3854	3791
	0,1	3042	2914	3075	2678	3027	3025	3062	3038
$g_к$	10	0,46	0,53	0,48	0,47	0,63	0,55	0,56	0,41
	1,0	0,42	0,53	0,44	0,37	0,54	0,47	0,44	0,34
	0,1	0,39	0,56	0,44	0,30	0,39	0,35	0,32	0,25
Mixture Charac-teristic	*P*, MPa	Be + $RbNO_3$	Be + NH_4ClO_4	Be + $KClO_4$	Ti + NH_4NO_3	Ti + $NaNO_3$	Ti + KNO_3	Ti + $RbNO_3$	Ti + Sr $(NO_3)_2$
$T_г$, K	10	4715	4216	5278	3779	4193	4147	4177	4598
	1,0	3791	3394	3912	3091	3291	3286	3292	3344
	0,1	3027	2812	3067	2529	2631	2630	2632	2663
$g_к$	10	0,40	0,31	0,47	0,72	0,68	0,63	0,49	0,76
	1,0	0,35	0,24	0,38	0,58	0,51	0,47	0,36	0,43
	0,1	0,25	0,17	0,25	0,47	0,38	0,35	0,27	0,31
Mixture Charac-teristic	*P*, MPa	Ti + Ba $(NO_3)_2$	Ti + NH_4ClO_4	Ti + $KClO_4$	Zn + NH_4NO_3	Zn + $NaNO_3$	Zn + KNO_3	Zn + $RbNO_3$	Zn + Sr $(NO_3)_2$
$T_г$, K	10	4514	4258	4785	1970	2516	2320	2286	2898
	1,0	3320	3255	3450	1583	2060	2047	2060	2204
	0,1	2644	2601	2699	1368	1664	1662	1665	1731

$g_к$	10	0,67	0,52	0,39	0,51	0,84	0,82	0,67	0,83
	1,0	0,33	0,34	0,16	0,37	0,77	0,74	0,62	0,69
	0,1	0,24	0,23	0,05	0,31	0,73	0,70	0,59	0,64
Mixture Charac-teristic	*P*, MPa	Zn + Ba $(NO_3)_2$	Zn + NH_4ClO_4	Zn + $KClO_4$	Zr + NH_4NO_3	Zr + $NaNO_3$	Zr + KNO_3	Zr + Sr $(NO_3)_2$	Zr + $RbNO_3$
$T_г$, K	10	2824	2799	3071	4320	4710	4693	4779	4700
	1,0	2196	2131	2204	3558	3944	3939	4002	3943
	0,1	1730	1692	1729	2950	3265	3264	3304	3266
$g_к$	10	0,85	0,43	0,64	0,80	0,73	0,68	0,65	0,57
	1,0	0,74	0,30	0,50	0,79	0,61	0,57	0,54	0,47
	0,1	0,68	0,24	0,45	0,75	0,51	0,48	0,45	0,40
Mixture Charac-teristic	*P*, MPa		Zr + $Ba(NO_3)_2$		Zr + NH_4ClO_4			Zr + $KClO_4$	
$T_г$, K	10		4770		4639			4920	
	1,0		3986		3759			4039	
	0,1		3293		3073			3296	
$g_к$	10		0,58		0,67			0,53	
	1,0		0,46		0,67			0,42	
	0,1		0,39		0,69			0,38	

Table 1 shows that one of the most characteristic features of the combustion of highly metalized pyrotechnic mixtures is a significant proportion of condensed combustion products, which can reach 0.76. It was also established that the maximum values of the temperature of combustion products ($T_{гmax}$) and the relative content of high-temperature condensate ($g_{кmax}$) at normal external pressure (P = 105) are observed at α = 0.95 ... 1.03. The equilibrium temperature of combustion products can vary in a wide range from 1375 to 5278 K, which is presented in the table 2.

From the data given in table 2, it is clear that, $T_{гmax}$ varies from 1373 K (for the mixture Zn + NH_4NO_3) to 5075 K (for the mixture Al + $KClO_4$), and $g_{кmax}$ – from 0,09 (for the mixture Ti + $KClO_4$) to 0,76 (for the mixture Zr + NH_4NO_3).

Table 2 – Value $T_{гmax}$ and $g_{кmax}$ for two-component pyrotechnic mixtures, metal fuel + oxygen-containing oxidizer

Mixture Charac-teristic	Mg + $NaNO_3$	Mg + KNO_3	Mg + $Ba(NO_3)_2$	Mg + $Sr(NO_3)_2$	Al + $NaNO_3$	Al + KNO_3	Al + $Ba(NO_3)_2$	AMC + $NaNO_3$
$T_{гmax}$, K	2535	2514	2551	2575	3045	3042	3063	2791
$g_{кmax}$	0,48	0,43	0,32	0,53	0,59	0,54	0,39	0,43
Mixture Charac-teristic	AMC + KNO_3	AMC + $Ba(NO_3)_2$	AMC + $Sr(NO_3)_2$	Mg + NH_4NO_3	Mg + $RbNO_3$	Mg + NH_4ClO_4	Mg + $KClO_4$	Al + NH_4NO_3
$T_{гmax}$,K	2789	2825	2807	2444	2535	2507	2669	2823
$g_{кmax}$	0,47	0,53	0,36	0,39	0,36	0,31	0,29	0,69
Mixture	Al + $RbNO_3$	Al + NH_4ClO_4	Al + $KClO_4$	Be + NH_4NO_3	Be + $NaNO_3$	Be + KNO_3	Be + $Sr(NO_3)_2$	Be + $Ba(NO_3)_2$

Characteristic								
$T_{гmax}$, K	3043	4539	5075	2673	3031	3028	3065	3043
$g_{кmax}$	0,40	0,55	0,51	0,32	0,42	0,37	0,34	0,24
Mixture Characteristic	Be + $RbNO_3$	Be + NH_4ClO_4	Be + $KClO_4$	Ti + NH_4NO_3	Ti + $NaNO_3$	Ti + KNO_3	Ti + $RbNO_3$	Ti + $Sr(NO_3)_2$
$T_{гmax}$, K	3032	2817	3073	2533	2632	2634	2635	2667
$g_{кmax}$	0,28	0,21	0,28	0,52	0,39	0,37	0,33	0,35
Mixture Characteristic	Ti + $Ba(NO_3)_2$	Ti + NH_4ClO_4	Ti + $KClO_4$	Zn + NH_4NO_3	Zn + $NaNO_3$	Zn + KNO_3	Zn + $RbNO_3$	Zn + $Sr(NO_3)_2$
$T_{гmax}$, K	2645	2603	2708	1373	1669	1665	1668	1735
$g_{кmax}$	0,26	0,25	0,09	0,33	0,74	0,71	0,62	0,67
Mixture Characteristic	Zn + $Ba(NO_3)_2$	Zn + NH_4ClO_4	Zn + $KClO_4$	Zr + NH_4NO_3	Zr + $NaNO_3$	Zr + KNO_3	Zr + $Sr(NO_3)_2$	Zr + $RbNO_3$
$T_{гmax}$, K	1734	1693	1733	2955	3267	3265	3305	3271
$g_{кmax}$	0,69	0,26	0,47	0,76	0,54	0,49	0,46	0,43
Mixture Characteristic	Zr + $Ba(NO_3)_2$			Zr + NH_4ClO_4			Zr + $KClO_4$	
$T_{гmax}$, K	3295			3076			3298	
$g_{кmax}$	0,40			0,71			0,42	

The study of pyrotechnic products made it possible to determine how the temperature T_g and the composition of combustion products depend on the technological parameters (the coefficient of excess oxidant α and its nature) and the pressure P of the external environment. It was found that the maximum temperature T_g reaches its maximum values at $\alpha = \alpha_{T_{rmax}}$ = 0,98…1,02 та $P = 10^5 \ldots 10^7$ Pa; and is $T_{гmax}$ = 2791…4532 K. An increase in external pressure at this same α leads to an increase in T_g and the content of high-temperature condensate g_k by 1.4...1.6 times, while with increasing dependence $T_g(P)$ та $g_k(P)$ are strengthened.

After analyzing existing data [1, 6], the possibility of formation of high-temperature condensed combustion products of metalized pyrotechnic mixtures was revealed. This is of important practical importance when assessing fire-hazardous situations arising from the premature activation of pyrotechnic products based on the specified mixtures in warehouses where they are stored, or during regular launch of products.

When metals burn, condensed substances are formed, which are separated from the gaseous phase in the combustion chamber or when the flow expands in the nozzle [1]. In this state, there may be metal oxides, carbon, as well as various technological and operational impurities, which are added to the mixture in the amount of 0.5-2% (soot, magnesium oxide, potassium chromate, etc.) [6]. This is important for assessing the risk of fire that may arise from the accidental release of metallized pyrotechnic products during their storage in warehouses or when the products are launched.

One of the key products formed during combustion and playing an important role in the formation of condensed combustion products is carbon. Its formation is carried out using reactions that can be described according to [1, 6].

One of the main chemical reactions that determines the composition of the combustion products of hydrocarbon fuel with an oxygen-containing oxidant is the reaction of water gas.

$$CO_2 + H_2 \rightleftarrows H_2O + CO. \quad (2)$$

Formation of atomic carbon from methane and its subsequent condensation [1, 6].

$$CH_4 \rightarrow C + 2H_2$$
$$C + O_2 \rightarrow CO_2$$
$$CO + O_2 \rightarrow CO_2$$

Therefore, with insufficient oxygen, methane may not be completely oxidized to CO_2, and as a result, soot is formed. Also, a large role in the formation of soot is played by the presence of impurities in the mixture of solid particles, such as metal powders, oxides and others

$$2CO \rightleftarrows CO_2 + C + 172{,}6 \text{ kJ}. \quad (3)$$

This process of formation of solid carbon usually occurs at fairly high temperatures (more than 1470 K) and relatively low pressure, which ensures the absence of condensation of combustion products. Carbon particles formed can contribute to the composition of condensed combustion products, as well as cause the formation of soot and other products.

During the burning of metallized pyrotechnic mixtures, aluminum agglomerates with sizes of 30...300 μm are formed on the burning surface [1, 6]. The process is accompanied by sintering of individual particles and their melting. The oxide film breaks down and drops appear that react chemically. It was noted that the ignition of the droplets occurs simultaneously with separation from the burning surface, however, in some mixtures, the droplets glow on the surface. The growth of condensed oxide particles occurs as a result of the deposition of vaporous matter and condensed nuclei according to complex laws. Experimental studies of these processes are extremely difficult due to the short duration, high pressures, temperatures and opacity of combustion products.

When burning pyrotechnic mixtures with metallized components, aluminum agglomerates with sizes of 30-300 microns are formed on the burning surface. The burning process is accompanied by sintering and melting of individual particles. In some mixtures, you can observe the glow of drops on the surface. The size of the agglomerates can reach 2000 μm with a high metal content in the mixture. With a metal content of more than 60%, the formation of a frame similar in shape to the original charge is possible. Oxide sizes in pyrotechnic mixtures are usually less than 1.7 microns, and 3% are in the range of 2-5 microns. [1, 6].

According to the research results, it was found that during the burning of pyrotechnic mixtures, the growth of condensed particles occurs, which is explained by the diffusion of substances to the nuclei during the movement of combustion products in the flame [6]. This process is also accompanied by aerodynamic forces that can cause deformation, crushing of large particles and coagulation of small ones. The size of the condensed particles can vary in the range from 0 to 13 μm, and the most likely distribution of particles by size satisfies the exponential law. [2]. The proposed physical model of particle growth in combustion products

explains that the nucleation rate is constant, and the growth rate is proportional to the concentration gradient and particle surface area. [1].

During the study of diffusion flames using dilute solutions, it was found that condensation nuclei, which have a wide range of sizes, are formed near the center of the flame. Currently, it is impossible to accurately calculate the rate of formation of nuclei and their distribution by size using numerical analysis methods, so empirical dependences are used in practice. For example, during the burning of metallized pyrotechnic mixtures, agglomerates can become condensation centers, dispersing from the burning surface into the flame zone.

When combustion products move in an accelerating flow, particles lag behind in speed, collide and merge into one larger particle [8]. However, when calculating the growth of particles during a longitudinal collision, it was found that the average diameter (about 11 μm) decreases by 2-3 times compared to experimental data.

Describing the process of particle growth during the combustion of metallized mixtures in rocket engines, it was found that most theoretical models predict the dominance of only one mechanism at any stage of the process [2]. All four variants of the models showed a maximum speed of particle growth and a decrease in their growth with decreasing particle concentration. No particular change in the size distribution of particles was observed during the collision, and the mechanisms of condensation and the effect of acoustic vibrations on the growth of particles can be considered secondary compared to collisions caused by a mismatch of particles in terms of velocities. The final size of the particles can change by 4-12% due to condensation and by 5% due to the effect of acoustic vibrations, and taking into account all processes occurring simultaneously can lead to an increase in the average diameter of oxide particles by 8-16%.

The presence of agglomerates of metal particles as a result of the combustion of metallized mixtures can lead to the danger of instability of the combustion process due to clogging of the combustion surface of the mixtures, which occurs when high-temperature, chemically active and significant condensate accumulates on it as a result of the fall of large agglomerates from the two-phase flow of combustion products.

It is worth noting that to date, researches concerning the mechanism of formation of agglomerates, their physicochemical properties and structure, as well as the influence of the agglomeration process on the combustion of pyrotechnic mixtures in various conditions are insufficiently studied.

In addition, thermodynamic calculations were performed in order to create a general database on the fire-hazardous properties of pyrotechnic products that contain aluminum-magnesium alloy powders and the nitrate-containing oxidizer ($NaNO_3$) widely used in pyrotechnics. These calculations made it possible to establish the temperature of combustion products depending on the ratio of components and environmental conditions, such as heating temperature and pressure, presented in the table 3 [2, 8, 9].

The calculations took into account the possibility of formation of only those gaseous and condensed products for which thermodynamic functions are now known: gases – $O^г$, $O_2^г$, $O_3^г$, $N^г$, $N_2^г$, $N_3^г$, $N_4^г$, $NO^г$, $NO_2^г$, $N_2O^г$, $Na^г$, $Na_2^г$, $NaO^г$, $Na_2O^г$, $Na_2O_2^г$, $Mg^г$, $MgO^г$, $Al^г$, $Al_2^г$, $AlO^г$, $Al_2O^г$, $AlN^г$; condensates – $Na^к$, $Na_2O^к$, $Mg^к$, $MgO^к$, $Al^к$, $Al_2^к$, $Al_2O_3^к$, $AlN^к$. According to calculations, gaseous and condensed combustion products contain ten-thousandths of a particle $N^г$, $NO_2^г$, thousandths – $Na_2^г$, $Na_2O^г$, $Mg_2^г$ $Al_2^г$, соті – $O^г$, $NO^г$, $NaO^г$, $Na^к$, $AlO^г$, the tenth – $O_2^г$, $O^г$, $N_2^г$, $Na^г$, $MgO^г$, $Al_2O^г$, $Mg^г$, $Na_2O^к$, $Mg^к$, $MgO^к$, $Al^к$, $Al_2O_3^к$, $AlN^к$.

Table 3 – Temperature dependence of combustion products ($T_г$, K) mixtures AMC + $NaNO_3$ from the oxidant excess coefficient (α)at different pressures (P, Pa)

α	P, 10^5 Pa			
	1	10	50	100
0,1	1690	1870	1960	2127
0,2	1759	1990	2250	2438
0,5	2620	2833	3083	3159
1,0	3334	3637	4042	4301
1,5	2916	3032	3130	3241
2,0	2670	2835	2963	3093
3,0	2451	2685	2705	2876
3,5	2125	2314	2470	2694
4,0	1873	2017	2184	2357
4,5	1680	1825	1948	2186
5,0	1463	1674	1797	1983

It also follows from these calculations that the qualitative and quantitative composition of the combustion products of mixtures is the strongest AMC + $NaNO_3$ depends on the coefficient of excess oxidant (under pressure $P = 10^5 \ldots 10^7$ Pa). At the same time, from the data on the composition of the main combustion products, the following characteristic ranges for α can be distinguished, which are shown in the table 4.

Table 4 – The qualitative composition of the final products of combustion of the mixture AMC + $NaNO_3$ at different values α and P

Range of change α	Range of change $T_г$ (K) under pressure $P = 10^5 \ldots 10^7$ Pa	The main products of combustion	
		Gaseous	Condensed
0,1...0,2	1690...2438	$Na^г$, $Mg^г$, $N_2^г$	$Mg^к$, $MgO^к$
0,2...0,5	2438...3159	$Na^г$, $N_2^г$, $Mg^г$, $Al^г$, $Al_2O^г$	$MgO^к$, $Mg^к$, $Al_2O_3^г$, $AlN^к$, $Al^к$
0,5...1,0	3159...4301	$Na^г$, $N_2^г$, $O_2^г$, $MgO^г$, $Al^г$, $O^г$	$MgO^к$, $Al_2O_3^к$
1,0...1,5	4301…3241	$Na^г$, $N_2^г$, $O_2^г$, $O^г$, $MgO^к$	$MgO^к$, $Al_2O_3^к$
1,5…2,0	3241…3093	$Na^г$, $N_2^г$, $O_2^г$, $MgO^г$	$MgO^к$
2,0…5,0	3093…3983	$Na^г$, $N_2^г$, $O_2^г$	$MgO^к$, $Na_2O^к$

Conclusions. The obtained results of thermodynamic calculations of temperature and composition of combustion products of pyrotechnic products are useful at the stage of development and their design. These results make it possible to predict possible fire-hazardous situations in the case of premature activation of products in the conditions of ignition of warehouses where they are stored, or during their regular start-up. Such conclusions can be important for ensuring safety during the production and use of pyrotechnic articles.

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ТЕРМОДИНАМІЧНІ РОЗРАХУНКИ ДЛЯ ВИЗНАЧЕННЯ ТЕМПЕРАТУРИ ПРОДУКТІВ ЗГОРЯННЯ ПІРОТЕХНІЧНИХ ВИРОБІВ НА ОСНОВІ ПОРОШКІВ АЛЮМІНІЄВО-МАГНІЄВИХ СПЛАВІВ

Дану статтю присвячено дослідженню пожежонебезпечних властивостей піротехнічних виробів на основі порошків алюмінієво-магнієвих сплавів з нітратовмісним окиснювачем ($NaNO_3$). У статті представлено термодинамічні розрахунки температури та складу продуктів згоряння цих виробів в залежності від співвідношення компонентів та стану навколишнього середовища. Отримані результати дозволяють визначати можливі пожежонебезпечні ситуації на стадії розробки та проектування піротехнічних виробів на їх основі. Така інформація допомагає запобігти можливим пожежам та нещасним випадкам при зберіганні та запуску піротехнічних виробів.

Ключові слова: *піротехніка, спалахувачі, згоряння, агломерати, термодинамічні розрахунки, пожежна безпека, складські приміщення.*