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Effect of Titanium (IV) Oxide on Composite Solid Propellant Properties

Vesna Rodić[1)]

The paper presents the research into the development of composite solid propellants based on hydroxyterminated polybutadiene including titanium (IV) oxide as not only a ballistic stabilizer but also a ballistic modifier of these propellant types. A number of different compositions regarding their solid content, coarse/fine ratio of ammonium-perchlorate powder sizes and titanium (IV) oxide content have been made for the research. The effects of titanium (IV) oxide, along with other ingredients of the propellant, on the apparent viscosity value, uniaxial mechanical characteristics, density, heat combustion and burning rate law parameters have been examined.

Key words: **composite rocket propellant, titanium (IV) oxide, propellant properties, ballistic properties, test results.**

Introduction

THE most frequent requirements for ballistic characteristics of rocket motors embedded with composite solid propellants (CSP) regard burning rate values at particular working pressures and pressure exponent as the burning rate law parameters. In the case of low burning rate propellants, the presence of some additives is necessary to obtain desirable ballistic properties. Besides that, it is important to eliminate unstable burning as a consequence of a higher binder content (propellant of limited properties).

Titanium (IV) oxide, TiO_2, reputes as very effective in almost all solid rocket propellants [1] and has sustained the plateau from 50 bar to 100 bar, especially in hydroxy-terminated polybutadiene (HTPB) systems where it enables stable burning in the wide range of pressures [2].

Except a good effect on the burning stability of CSP, some new aspects of the titanium dioxide role have been detected [3]. The development of new CSPs of low burning rates, pressure exponents and sensitivity to pressure and temperature changes has been attempted in this work. The other propellant components could be combined, depending on requirements.

Theoretical part

The refractory oxides, such as zirconium (IV) oxide (ZrO_2), aluminium (III) oxide (Al_2O_3), silicon (IV) oxide (SiO_2) and TiO_2 are used because of their ability to affect the combustion process of CSP by forming a plateau in the compositions of wide distribution of ammonium-perchlorate (AP) particle sizes. The appearance of a plateau is much too often with doublebase propellants, while it is a hard working in the case of CSP. Many other factors affect the extent of the plateau range and its position: plasticizer quantity, powder size of refractory oxide, distribution of AP coarse /fine particles and an isocyanate curing agent [3].

TiO_2 (melting temperature: 1870ºC), added to a CSP based upon HTPB, acts to increase the binder melt layer viscosity restoring normal burning at low and high pressures, leaving abnormal burning of a solid propellant, thereby preventing stirring with fine AP particles and enables the plateau effects at intermediate pressures. It has been concluded that TiO_2 is a positive catalyst for decomposition but at pressures well below those where the burning plateau has been observed (50 - 100 bar). It has been speculated that, if the same observations aree valid at higher pressures, then TiO_2 may dampen the amount of heat released and contribute to a reduction of the burning rate, so it can also be used for the pressure exponent equalization. It has been suggested that the amount of TiO_2 in the CSP should be from 1 - 2%. The addition of 2% provides the most distinctive plateau. In pyrolysis experiments of AP/HTPB mixtures, an accelerated rate of evolution of gaseous products was reported when 5% was added [2].

By increasing the oxide level, the burning rate decreases, so it is useful for improving or controlling different ballistic performances (as a burning rate level stabilizer or modifier) [4]. The quantities up to 1.5% have been used in this research, since the propellants of low AP content have been investigated.

Moreover, other ingredients have a large influence on the propellant combustion, so it is necessary to know how to improve desirable properties.

It was also noticed that higher content of plasticizer improved the plateau level determination. Decrease of AP content or additives reduces the burning rate and diminishes the plateau range. The microscopic images of coarse AP (200 μm) and fine (milled) AP (7 μm) particles are shown in Figs. 1 and 2, respectively.

1) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

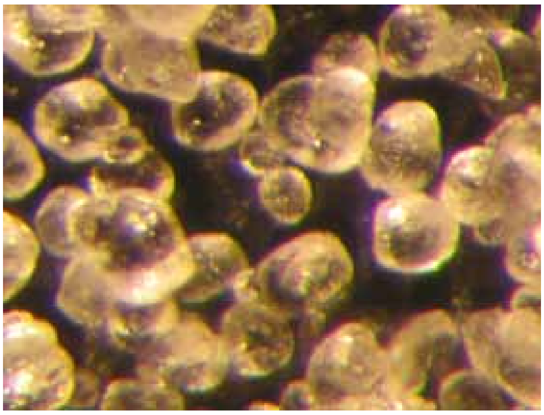

Figure 1. Coarse AP (200 μm)

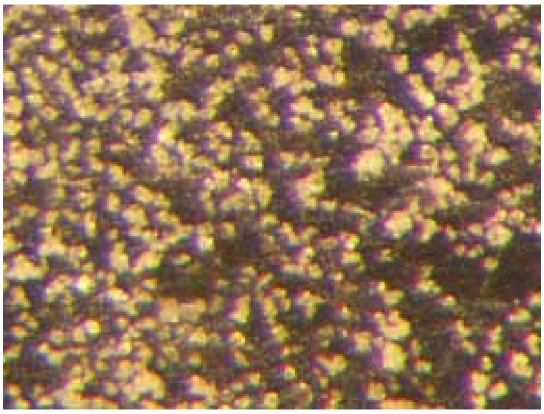

Figure 2. Fine AP (7 μm)

General characteristics of combustion with a bimodal AP mixture, with a simple view of the combustion zone in Fig.3 [4] can be a very helpful overview. A burning surface consists of fields of large oxidizer particles surrounded by a layer including a mixture of binder and AP fine particles (called "matrix"). At a first glance, one might say that large particles and the AP matrix burn independently. However, this does not happen because burning large particles are covered with burning matrix vapor.

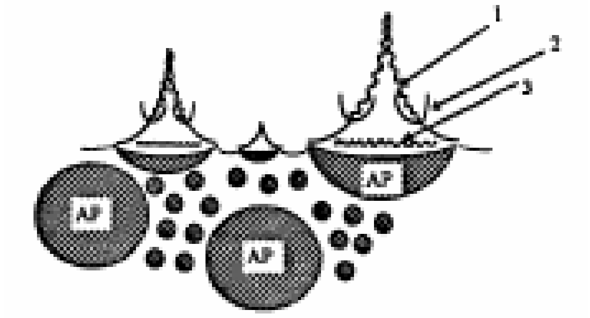

Figure 3. Propellant combustion zonet with bimodal AP

where is:

1. restricted diffusion flame mixture of AP/binder;
2. boundary layer flame;
3. deflagration flame of AP particles (instantly burning).

During CSP combustion, the changes in the large and fine particle content contribute to various spacing of large particles and a mixture oxidizer/binder in the matrix. It is very important to ensure a certain gap responsible for depressive burning due to the involved fine AP that burns with a layer of melted binder. This is achieved by a wide particle size distribution of the AP with the correct ratio of large and fine particles and the relative size of the particles of both fractions [2]. Therefore, when the ratio of large/fine AP particles increases to the point where the space between large particles becomes significant, the burning of small particles will be inhibited by melted coating binders. The consequence is the appearance of depressive combustion; in extreme cases, the "binder/fine AP" matrix can prevent continued burning and occurrence of instability. This can be eliminated by the addition of TiO_2. The particle size of fine AP contained in the matrix significantly affects the whole system and its balance.

All physical processes and chemical reactions take place simultaneously or successively. The development rate of these processes and their energy characteristics determine the rate of combustion, surface temperature, flame height and appearance of the burning surface.

Some investigations of melt flows formed the basis for the determination of the effect of a binder-curative system on the plateau burning in composite propellants [2]. For example, the HTPB/dimeryl diisocyanate (DDI) binder system was observed to melt at 260ºC to a low viscosity fluid, well below the vaporisation temperature (500ºC). Other curative agents used with HTPB, ranked in order of melt state temperature, were toluene diisocyanate (TDI, 300ºC), isophorone diisocyanate (IPDI, 330-370ºC) and methyl diphenyl diisocyanate (MDI, 400ºC) [5]. The large difference in melt and vaporisation temperatures was assumed to indicate a relative thickness of the binder melt layer in CSP. The ability of the HTPB binder to melt could be tailored by choice and a combination of curing agent(s). In addition, more severe anomalous combustion and lower burn rates were observed in the propellants of wide oxidizer particle size distribution containing DDI than in those containing IPDI. It was found that IPDI was more effective in restoring normal burning than DDI and assumed that this indicated an ability of the matrix to burn ahead of the coarse AP. CSPs containing DDI exhibit bi-plateau burning, an additional plateau forming at low pressure (14 - 48 bar) [2].

Therefore, the selection of different propellant ingredients and their content has a large influence on propellant combustion.

Experimental part

The aim was to obtain a propellant of low burning rates (v < 4.3 mm/s at p < 60 bar), with pressure exponents (n < 0.25) and temperature sensitivity (σ < 0.0012 1/ºC), using titanium-dioxide.

Ten compositions of different solid content and ratios of bimodal AP fractions, each of them including TiO_2 and two with lithium fluoride (LiF) as a burning rate depressant, were based on HTPB and isophorone-diisocyanate (IPDI) as a curing agent.

Figure 4. Laboratory vertical planetary mixer bowl

All ingredients were homogenized at 50ºC in the laboratory vertical planetary mixer, Fig.4. All the compositions are shown in Table 1.

Table 1. Compositions of CRP

Batch No	TiO_2, (%)	LiF, (%)	AP, (%)	AP_{200}/AP_{10}
56	1.5	-	76.0	80/20
57	1.0	0.7	73.0	75/25
58	1.5	-	73.5	80/20
59	1.0	0.5	73.0	70/30
60	1.2	-	72.5	75/25
61	1.5	-	72.0	79/21
62	1.2	-	72.0	76/24
63	1.0	-	71.5	76/24
65	1.2	-	72.0	76/24
66	1.0	-	71.5	76/24

Afterwards, the propellant was cast in the casting tools shown in Fig.5 for the static tests. The cylindrical grains were machined after a curing period and dismantling the tools resulted in small ring-rollers with the following dimensions defined for burning rate law determination: external diameter, D = 21 mm, internal diameter, d = 7 mm and roller hight, L = 15.3 mm. Up to 4 ring-rollers were made from each composition from Table 1, depending on the characteristics.

Figure 5. Casting tools for ballistic determination

The cured piece of propellant is shown in Fig.6.

Figure 6. Propellant after a curing period

Results of examinations

Uniaxial mechanical characteristics were measured on the universal tester type Instron 1122 on a JANAF "C" specimen (effective gauge length, l_0 = 68.6 mm), at a tension rate (crosshead speed) of 50 mm/min and at room temperature (20±2)ºC.

The following uniaxial mechanical characteristics have been determined:

- maximum stress or tensile strength, σ_m,
- strain at maximum load, ε_m and
- Young`s modulus of elasticity, E.

The results of the examination are given in Table 2. The density values of the propellant specimens were measured by Mohr balance and heat capacity was measured by an IKA C400 adiabatic calorimeter. These results are shown in Table 3.

Table 2. Mechanical characteristic values

Batch	σ_m (daN/cm^2)	ε_m (%)	E (daN/cm^2)
56	5.34	12.14	57.49
57	5.35	16.27	42.26
58	4.88	13.24	47.98
59	5.48	16.55	42.81
60	4.39	22.74	32.34
61	4.71	13.78	40.25
62	4.35	13.46	42.15
63	4.12	13.88	37.53
65	3.91	14.10	22.63
66	3.82	14.41	22.89

Table 3. Density and heat capacity values

Batch	Density (g/cm^3)	Heat capacity (J/g)
56	1.568	-
57	1.531	-
58	1.536	3562
59	1.528	3610
60	1.515	3494
61	1.516	3508
62	1.510	3537
63	1.500	3554
65	1.511	3616
66	1.502	3595

The experimental motor for burning rate law determination, named here SWF, is shown in Fig.7.

There are two nozzles of 1.3 mm in diameter on the motor. A desirable range of working pressures could be attained by changing the values of external and internal diameters, but with a constant grain height. The adjustment of the pressure extent could be done using one or both nozzles or using 2, 3 or even 4 smaller rollers, depending on propellant properties.

The point is to provide the burning rate law parameters by a digressive combustion mode from only one test.

Figure 7. Experimental SWF motor

Table 4 shows the burning rates (v) at the mean calculated pressure (p_m) and the pressure exponent (n) from the burning rate law at room temperature. The last two tests are the examinations performed using only one nozzle d=1.3 mm, labelled with *. The mean pressure values are increased.

Table 4. Burning rate law parameters at 20ºC

Grain	P_m (bar)	v_m (mm/s)	n	R^2
56/1	42.14	5.40	0.1962	0.9185
57/1	41.22	4.99	0.5515	0.9792
58/1	35.17	4.35	0.2829	0.9467
59/1	35.81	4.36	0.4895	0.9888
60/1	32.21	3.67	0.3457	0.9314
61/1	30.94	3.67	0.3941	0.8813
61/2	34.93	3.88	0.4404	0.9835
61/3	28.79	3.64	0.3862	0.9620
62/1	32.67	3.75	0.2518	0.9057
62/2	32.26	3.74	0.2858	0.9340
62/3	35.32	3.86	0.2580	0.9092
62/4	29.79	3.75	0.3243	0.9291
63/1	29.50	3.45	0.1922	0.7949
63/2	30.71	3.39	0.2223	0.8518
63/3	31.71	3.76	0.2966	0.9313
65/2*	81.82	4.55	0.1856	0.8584
66/2*	69.45	4.20	0.2085	0.8962

Some of the compositions were tested at -32ºC and 60ºC and these results are given in Table 5. Compositions No 65 and 66 are the same as 62 and 63, respectively, because of detailed characterization.

Table 5. Burning rate law parameters at -32 ºC and 60 ºC

Grain label	T_{exp} (ºC)	Δp (bar)	P_m (bar)	V_m (mm/s)	n	R^2
62/5	60	20 ÷ 45	34.22	3.93	0.2612	0.9266
63/4	60	20 ÷ 50	34.48	4.07	0.2367	0.9173
65/1	-32	20 ÷ 45	33.35	3.74	0.3457	0.9540
66/1	-32	15 ÷ 40	27.88	3.42	0.3206	0.9274

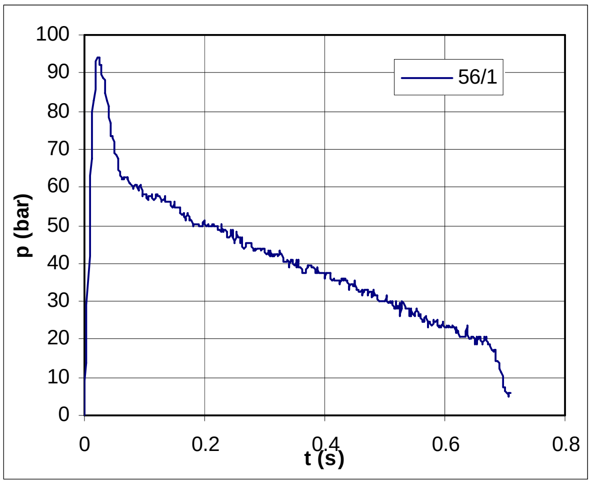

Figure 8. Pressure – time dependence at 20 ºC

The pressure-time dependence plot, given in Fig.8, is an example of digressive combustion for the grain (roller) 56/1, but it is distinctive for all formulations, except for the batches Nos 57 and 59. These two types of propellant consisted of LiF as a ballistic modifier, besides titanium-dioxide (Table 1).

The presence of LiF generates a kind of a "saddle" on the chart, the change of the curve slope, batch 57 in Fig.9. As the amount of LiF is higher, the cavity is deeper.

Because of that, these types of propellant, consisting of LiF, (e.g. CSP for antihail propulsive charges), could be unstable during combustion especially at low operating temperatures.

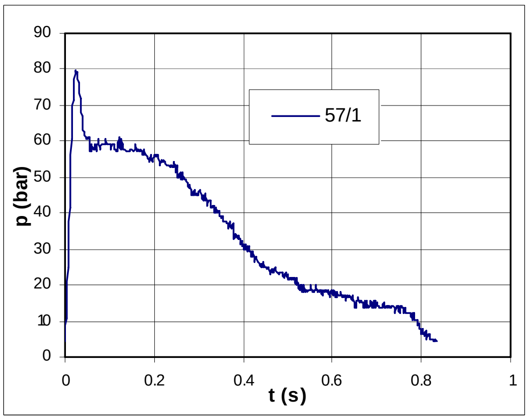

Figure 9. Pressure – time dependence (with LiF)

Discussion

The values in Tables 2 and 3 are expected for low solids content compositions of CSP. In order to improve the casting quality of 65 and 66 compared to 62 and 63, respectively, a large amount of plasticizer was added to the mass, which caused a slight decrease in the tensile strength (maximum stress) values. In the case of the composition of extremely small share of solid phase, during the curing period there is a great sedimentation of solid particles. This concerns AP in particular, because the coarse fraction of the oxidizer contains more than 70% of particles larger than 150 μm which tend to fall to the lower layers of cast blocks of propellants or grains. Therefore, the type and amount of liquid components "condensed" the whole system and made the process of sedimentation slow down.

The role of titanium-dioxide in CSP has already been examined [3], but the compositions in this paper were considered for the first time.

At the very beginning of our ballistic examination, it was important to determine the range of attained pressures as well as the proper combustion. These burning rate laws are shown in Fig.10. Batches Nos 56, 58 and 60 are almost parallel (1.2 – 1.5 % TiO_2), but the burning rate levels depend on AP content only.

The decrease of the oxidizer content conducted to the decrease of the upper pressure limit as well and the displacement of the working pressure range to the left.

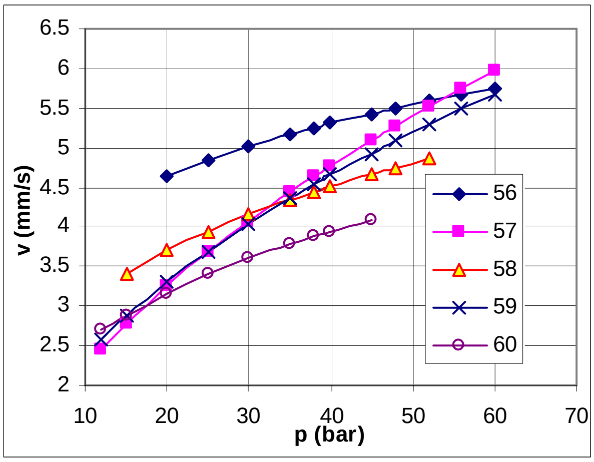

Figure 10. Burning rate laws for the first five batches

The other already mentioned batches, 57 and 59, have 1 % of TiO_2. They cover a wider pressure area but with higher exponent values than Nos 56, 58 and 60.

Obtaining quite lower burning rates, besides implied steady combustion at low pressures, it was tried to realise in the following examples owing to dual TiO_2 roles.

Fig.11 shows the plot of the burning rate laws of two batches consisting of 72 mas.% AP both.

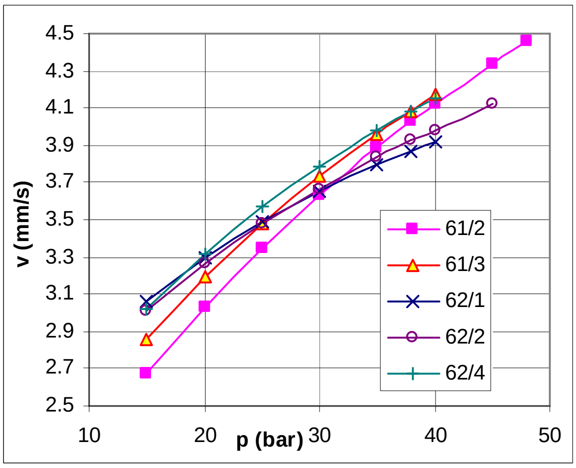

Figure 11. Burning rate laws for Nos 61 and 62

A difference of these two compositions is noticed between the exponent levels. The plots from one batch are analogous. Some small deviations (about 5%) within No 62 appeared by increasing pressure from 15-20 bar to 40 bar. The lower exponents are explained by a better AP ratio (AP_{200}/AP_{10}) which is closer to a theoretically ideal one - 65/35, Table 1. Because of the lower rates and exponents (p > 30bar), batch 62 is more interesting.

The effect of additives on ballistic parameters is stronger if the AP fraction ratio (coarse vs. fine particles) is lower; therefore, a more significant effect of TiO_2 can be expected with a larger content of fine AP particles in the bimodal mixture. Since this solid content of CSP has not been examined previously in our country, it is not possible to know the exact optimal ratio between an oxidizer and titanium-dioxide. Therefore, there is only a presumption that it is closer to composition 62.

Composition 63 was prepared and tested corresponding to successive decreasing of the burning rate by the AP content reduction and the maintenance of the AP/TiO_2 ratio. The testing results of Nos 62 and 63, with a good reproducibility, are shown in Fig.12.

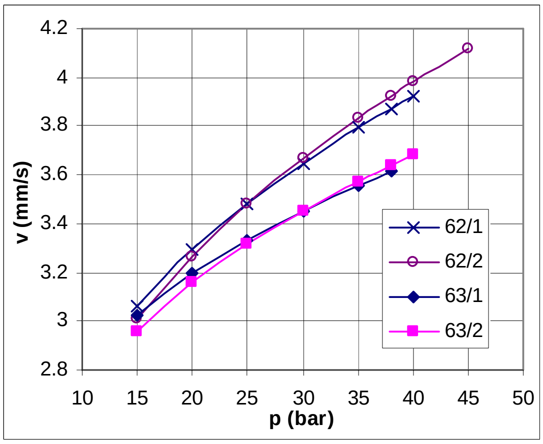

Figure 12. Burning rate laws for No 62 and 63

Table 6. The burning rates at the value p_m* (33.55 bar)

Grain label	V_m (mm/s)	n	B
56/1	5.13*	0.1962	2.5734
57/1	4.33*	0.5515	0.6238
58/1	4.29*	0.2829	1.5871
59/1	4.27*	0.4895	0.7647
60/1	3.73*	0.3157	1.2298
61/1	3.88*	0.3941	0.9721
61/3	3.89*	0.3862	1.0029
61/2	3.81*	0.4404	0.8114
62/2	3.79*	0.2858	1.3874
62/1	3.75*	0.2518	1.5495
62/3	3.76*	0.2580	1.5195
62/4	3.92*	0.3243	1.2557
63/1	3.53*	0.1922	1.7962
63/2	3.54*	0.2223	1.6217
63/3	3.83*	0.2966	1.3508
65/2 (1×1.3)	4.40**	0.1856	1.9724
66/2 (1×1.3)	4.30**	0.2085	1.7453

Table 6 shows all the parameters of the burning rate laws for each considered formulation at 20ºC.

It has to be mentioned that the last two examinations were carried out at regimes different from the others, as follows:

* at calculated pressure p_m = 33.55 bar; (2×1.3)
** at calculated pressure p_m = 75.65 bar; (1×1.3)

A pressure of 33.55 bar is calculated from the mean pressure values of all tests at 20ºC using two nozzles (2×1.3 mm, Table 3). The burning rates for No 62 are in the range from 3.75 to 3.79 mm/s and in the range from 3.53 to 3.54 mm/s for No 63.

The solid phase and the AP content in all the compositions determined lower burning rate levels, so it seems as if the effect of TiO_2 is of minor importance. However, its effect on the exponent pressure is significant. The differences are more visible during the examination of larger pressure range formulations or when using different nozzle diameters. Therefore, the further tests were carried out using only one nozzle of 1.3 mm and the calculated mean pressure of these two tests was 75.65 bar. Titanium-dioxide affects the extension of the working pressure area and the reduction of the pressure exponent.

The burning rate values at the calculated mean pressures and two testing extreme temperatures: 34.35 bar (at 60°C), 30, 60 bar (at -32ºC), from Table 6 are shown in Table 7, including again other burning rate law parameters.

Table 7. Burning rate values at the calculated mean pressures at extreme temperatures

T (ºC)	Grain label	V_m (mm/s)	n	B
60	62/5	3.95*	0,2612	1,5701
	63/4	4.05*	0,2367	1,7527
-32	65/1	3.60**	0,3457	1,1029
	66/1	3.54**	0,3206	1,1834
* at calculated p_m = 34,35 bar;		** at calculated p_m = 30,60 bar		

Burning rate laws at three different testing temperatures of the same formulations are represented in Figs. 13 and 14. It has to be mentioned that formulations 62 and 63 are the same as 65 and 66, respectively.

In according to some divergention of the results because of distinctions among the internal diameter of testing roller it has to take care about that.

It could be seen from Figs. 13 and 14 that the short range of the mean pressure values, depending on temperature, corresponds to the same nozzle dimension tests (2×1.3mm).

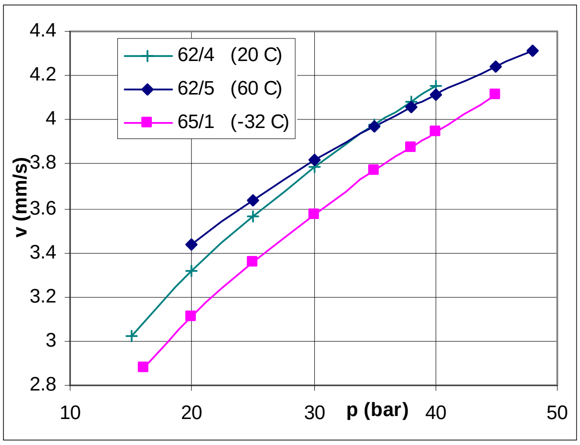

Figure 13. Burning rate laws No 62/65 at three temperatures

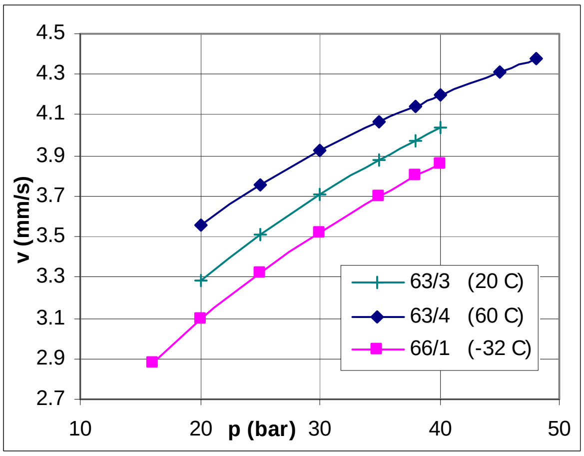

Figure 14. Burning rate laws No 63/66 at three temperatures

Thus, it is possible to compute temperature sensitivity at constant pressure (average pressure value in the whole temperature range =32.83 bar≈33 bar) using equation (1):

$$\sigma_p = \frac{\ln\left(v_2/v_1\right)_p}{T_2 - T_1} \tag{1}$$

where:

- v_1, v_2 [mm/s], - burning rates at a corresponding pressure value "p" at T_1 and T_2;
- T_1, T_2, - test temperatures, (-30ºC and 60ºC) respectively,
- p, average pressure value in the whole temperature range (33 bar).

The results of these evaluations for both compositions are given in Table 8.

Table 8. Temperature sensitivity of two compositions at the mean pressure value

Batch	σ_{33} (1/ºC)	-32ºC			60ºC		
		V_{33} (mm/s)	B	n	V_{33} (mm/s)	B	n
62/65	0.00063	3.69	1.1029	0.3457	3.91	1.5701	0.2612
63/66	0.00108	3.63	1.1834	0.3206	4.01	1.7527	0.2367

The attained temperature sensitivity values are certainly very important and many demands are based upon this CSP property: the most frequently required values are ≤ 0.12 %/ºC, so a significant effect of titanium-dioxide is obtained.

Conclusion

The research described in this paper regards the development of composite solid propellants including ammonium-perchlorate as an oxidizer, a binder based upon hydroxyl-terminated polybutadiene and titanium-dioxide as a ballistic stabilizer and a modifier of these types of propellants for burning rate decrease. Most of the considered compositions, including a small part of solid phase, were made in our place for the first time.

Ten compositions of different solid content and ratios of bimodal AP fractions, each of them including TiO_2 and two with lithium fluoride (LiF) as a burning rate depressant, were based on hydroxyl-terminated polybutadiene (HTPB) and isophorone-diisocyanate (IPDI) as a curing agent.

The uniaxial mechanical properties, density and heat combustion were measured for the propellant specimens and all the results are expected for the propellants of small solid phase quantity.

Static tests in the experimental motor with two nozzles of 1.3 mm were used together with the cylindrical propellant grains (a different range of pressure values was attained by changing the external and internal diameter values) for the burning rate law determination. The law parameters were determined by degressive combustion from one test and a grain of 6.5 g, while for the 2 inch experimental motor a 350 g are needed.

All the ballistic tests were carried out at room temperature, except for two at extreme temperatures (-32ºC and 60ºC). The adjustment of the pressure extent (the initial cross-section area) was done using one or two nozzles or changing the grain dimensions. The temperature sensitivity (σ_p) is calculated for the average value of the whole pressure range from -32ºC to 60ºC.

All the prepared compositions have shown a large stability during combustion. The effect of titanium-dioxide is especially noticeable at very low pressure values, involving stability, ignition facility, decreasing the exponent value in the large working pressure area (with the adequate nozzles), according as the realization of very low burning rates. All the burning rate law parameters of batches including the low content of both an oxidizer and a solid phase (very close to undermost limit) have been hardly achieved with the bimodal fractions of 200 and 10 μm of ammonium-perchlorate and without TiO_2. It was quite noticeable that the effect of ballistic additives (regardless of their type) is more significant if the coarse and fine oxidizer ratio is lower. It means that the influence of TiO_2 will be larger in the mixture including a finer AP fraction. It is recommended to use mixtures very close to optimal (65/35 for 200/10) ones. However, because of the very beginning in the field of low AP content, it was better to try with AP_{200}/AP_{10}=76/24 in the 72 mas.% of AP besides 1-1.2 mas.% TiO_2.

Propellants including LiF could not comply with all of these requirements, especially because of ignition problems [6].

In addition, a very important value is temperature sensitivity which is smaller than those often given as referent ones in the cases of propellants including titanium-dioxide.

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Uticaj titan (IV) oksida na karakteristike kompozitnih raketnih goriva

U radu su prikazana istraživanja vezana za razvoj kompozitnih raketnih goriva na bazi hidroksiterminiranog polibutadiena koja sadrže aditiv titan (IV) oksid ne samo kao balistički stabilizator, već i kao balistički modifikator ovih vrsta raketnih goriva. Izrađeno je više sastava međusobno različitih u odnosu na sadržaj čvrste faze, odnos krupnih i sitnih čestica amonijum-perhlorata, kao i udela titanijum-dioksida. Takođe su ispitivani uticaji samog aditiva i drugih komponenata goriva na vrednosti prividnog viskoziteta, jednoosnih mehaničkih karakteristika, gustine, toplotnog potencijala, kao i parametara zakona brzine sagorevanja.

Ključne reči: **kompozitno raketno gorivo, titan (IV) oksid, karakteristike goriva, balističke karakteristike, rezultati ispitivanja.**

Влияние оксида титана (IV) на характеристики мнолокомпонентных ракетных топлив

Эта работа описывает исследования по разработке мнолокомпонентных ракетных топлив на основе добавки гидроокиси полибутадиена, содержащих оксид титана (IV) не только в качестве баллистического стабилизатора, но и в качестве баллистического модификатора этих видов ракетных топлив. Изготовлено выше составов, которые становятся ещё более отличающимися друг от друга в зависимости от содержания твёрдой фазы, от соотношения крупных и мелких частиц перхлората аммония, а в том числе и от доли диоксида титана. Кроме того, исследовны и эффекты самого оксида титана (IV) и добавок и других компонентов топлива на значения кажущейся вязкости, одноосных механических свойств, плотности тепловых потенциалов, а также и параметров закона скорости горения.

Ключевые слова: **мнолокомпонентное ракетное топливо, оксид титана (IV), характеристики топлива, баллистические характеристики, результаты тестов.**

L'effet du titane oxyde sur les caractéristiques des propergols composites

Ce papier présente les recherches concernant le développement des propergols composites basés sur le polybutadiène hydroxi terminé qui contient l'aditif titane (IV) oxyde non seulement comme le stabilisant balistique mais aussi comme le modificateur balistique de ces types de propergols. On a fait plusieurs compositions mutuellement différentes par rapport au contenu de la phase solide , au rapport des particules grosses et petites de l'ammonium perchlorate ainsi que du partie de titane dioxyde. On a étudié également les effets de l'aditif même ainsi que les effets des autres composantes du propergol sur les valeurs de la viscosité apparente , des caractéristiques mécaniques uniaxes , de la densité, du potentiel thermique et les paramètres de la loi de la vitesse de combustion.

Mots clés: **propergol composite, titane oxyde, caractéristique du propergol, caractéristiques balistiques, résultats des essais.**