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Influence of Technological Parameters on the Combustion Velocity of Pyrotechnic Compositions for Gas Generator of Base Bleed Projectiles

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Abstract: The specific purpose of a pyrotechnic mixture for a Gas Generator (GG) of Base Bleed (BB) projectile requires a carefully balanced combustion velocity for obtaining the maximum projectile range and avoiding a reactive propelling force. The development of the pyrotechnic element is done under laboratory conditions which often differ from the real usage conditions. To be able to fairly predict the combustion process characteristics in the real GGs of BB projectiles, some influential technological factors and their influence on the combustion velocity have been investigated. Factors which were observed to have the most significant influence on the combustion velocity of pyrotechnic compositions are charge density, oxygen balance, combustion chamber wall thickness and material type. Individual and combined influence of these factors on the combustion velocity will also be presented in this paper.

Keywords: energetic materials, pyrotechnic compositions, gas generator charge, base bleed projectiles, combustion stability

1 Introduction

In the past few years both metallic and organic fuel of pyrotechnic mixtures for 37 mm anti-air BB projectiles have been the subject of investigation in the

Military Technical Institute in Belgrade. Previous investigation results had highlighted some concerns which needed to be investigated:

- Both organic and metallic based pyrotechnic charges showed an increase in burning velocity when pressed into steel wall charge casings instead of aluminum tubes which are commonly used in the developmental phase in the laboratory.
- Field test data analysis of fired 37 mm AA BB projectiles showed that, although, magnesium based GG charges were energetically stronger than lactose based ones, due to the increased mass of combustion products and the formation of magnesium conglomerates that were pulled away from the combustion zone by centrifugal forces, their combustion stability was undermined.
- Field tests also showed that organic based GG pyrotechnic charges (represented by lactose based compositions) had better overall characteristics (ignition even with 2 grams of igniting composition, burned without flame blast and sustained stable combustion throughout the whole projectile flight).

2 Theoretical Considerations

The understanding of a pyrotechnic reaction can sometimes be very difficult, because in solid state chemistry, factors such as particle size, impurities and oxidation layers on the surface of the fuels significantly influence the reactions' behaviour. A pyrotechnic composition must be capable of undergoing reliable ignition when an ignition stimulus is provided and sustain stable combustion under all usage conditions. We can differentiate two stages of combustion for all pyrotechnic compositions:

- initiation – the ability of the pyrotechnic composition to ignite under external stimulus, and
- propagation – the ability of the composition, once ignited, to sustain or propagate the burning process through the remainder of the composition.

These two processes share a number of common factors, but there are also some differences related to the involvement of the external and internal energy. For example, in order to ignite some pyrotechnic compositions, a portion of the mixture must be heated to its ignition temperature, which is defined as the minimum temperature required for the initiation of a rapid, self-propagating exothermic reaction. Upon ignition, the reaction should proceed on its own through the remainder of the pyrotechnic composition in the absence of any input of additional external energy. The heat released by the occurrence of the high-energy reaction raises the temperature of the next layer or grain of the composition. If the heat evolution and thermal conductivity are sufficient to supply the required activation energy (via the temperature increase) to the next layer, further reaction will occur, liberating additional heat, and propagation of the reaction through the mixture takes place. The rate and quantity of heat transfer to, heat production within, and heat loss from the pyrotechnic composition are all critical factors in achieving and sustaining propagation of combustion via self-sustaining chemical reactions [1].

Aside from these factors, the other challenges in developing base bleed charges are the large set back forces (up to 18000 g), the high rate of spinning of the shell (200-300 s^{-1}), as well as the pressure drop upon firing the shell, which may cause quenching of the combustion [2]. To be able to develop pyrotechnic compositions with the best characteristics under real life usage conditions, all of the influential factors on its combustion process have to be investigated.

3 Experimental

Obtaining representative data was done through a process of carefully defining the mixture ingredients and their portions. The influence of every factor on the burning velocity was investigated. The investigation results were subjected to a thorough analysis, and furthermore, a variation coefficient was introduced as a criterion of data validity. The variation coefficient, for every individual pyrotechnic composition, is defined as a standard deviation to average combustion velocity ratio, multiplied by 100 to obtain some meaningful and comparable shape (see the Equation 1).

$$VC = Sd/BVav \times 100 \tag{1}$$

where:

VC – variation coefficient; Sd – standard deviation, and BVav – average value of burning velocity.

It represents the validity of the results and is a measure of the homogeneity of the pyrotechnic mixture. A variation coefficient below 10, indicates that good representative data were obtained. A value of the variation coefficient below 5 is something that every researcher aims for when conducting any experiment, because it allows the best data comparison and validity of conclusions based upon those results.

The data analysis was done through a comparison of the linear burning velocity, because this combustion characteristic is the most dependable on the technological parameters investigated in this paper. Also, the linear burning velocity regulates the amount of gaseous products, in a defined period of time, released through combustion of the GG charge, which is crucial for the enhancement of a projectile's range.

The investigation of the effect of a specific parameter on the linear burning velocity was done by eliminating the influence of the other technological parameters. For example, if the influence of charge density on the burning velocity and the thermokinetics of the mixture were investigated, pyrotechnic compositions with the same oxygen balance were used, *etc*.

3.1 Defining a composition for investigation

Analysis of the research results in a previous phase had indicated the significant influence of several parameters that needed further investigation. Therefore several pyrotechnic compositions were defined and produced in order to investigate the influence of those parameters on the burning velocity.

The mixture ingredients are presented in Table 1.

Table 1. Defined pyrotechnic compositions for investigation

Comp. label	Ingredient/ mass portion [%]			Oxygen balance [%]
	Fuel	Oxidizer	Binder	
Neutral oxygen balance				
010/12	Lactose / 27.6	$KClO_4$ / 69.4	Viton A / 3.0	0.06
006/12	Lactose / 26.8	$KClO_4$ / 69.2	Viton A / 4.0	-0.02
001/12	Lactose / 26.1	$KClO_4$ / 68.9	Viton A / 5.0	-0.70
004/12	Lactose / 25.2	$KClO_4$ / 68.8	Viton A / 6.0	0.06
005/12	Lactose / 24.4	$KClO_4$ / 68.6	Viton A / 7.0	-0.02
013/12	Ascorbic acid / 30.9	$KClO_4$ / 66.1	Viton A / 3.0	-0.26
012/12	Ascorbic acid / 30.0	$KClO_4$ / 66.0	Viton A / 4.0	-0.33
007/12	Ascorbic acid / 29.1	$KClO_4$ / 65.9	Viton A / 5.0	-0.46
011/12	Ascorbic acid / 28.0	$KClO_4$ / 66.0	Viton A / 6.0	0.46
Positive oxygen balance				
002/12	Lactose / 22.9	$KClO_4$ / 71.8	Viton A / 5.3	15.24
008/12	Ascorbic acid / 25.9	$KClO_4$ / 69.1	Viton A / 5.0	15.52
Negative oxygen balance				
003/12	Lactose / 29.3	$KClO_4$ / 65.7	Viton A / 5.0	-14.39
009/12	Ascorbic acid / 32.5	$KClO_4$ / 62.5	Viton A / 5.0	-14.26

As can be seen from the data in Table 1, the percentage of fuel and oxidant was varied to gain the desired oxygen balance and to be able to observe its influence on the combustion velocity, and heat transfer through the mixture itself, through the GG chamber walls to adjacent mixture layers and to the surroundings.

3.2 Investigation of the influence of the thickness of the GG chamber walls on the combustion velocity

Heat transfer through the GG pyrotechnic charge is of greatest importance to its combustion stability, because disruption or minimization of heat transfer from the combustion zone to the layers beneath that zone, due to heat loss through the GG chamber walls, could jeopardize the stability of the combustion process or even make it entirely impossible. The amount of heat needed for a stable combustion process depends mostly on the mixture composition, whether it has a high energy fuel or an organic one, or whether the oxidizer lowers the ignition temperature ($KClO_4$) or exhibits a highly endothermic decomposition process (KNO_3), *etc*. Having these factors in mind, it could be safely said that heat loss through the GG chamber walls could pose a great threat to combustion stability if the amount of heat transferred to layers beneath the combustion zone were less than needed for stable combustion.

To obtain the critical information needed to make proper conclusions, all of the pyrotechnic compositions from Table 1 were pressed into aluminum tubes with 1 and 2 mm thick walls.

3.3 Combustion process characteristics

3.3.1 Burning velocity

The burning velocity is a very important characteristic for all pyrotechnic mixtures. Since GG mixtures have to generate specific amounts of gaseous combustion products in time in order to annul the reduced pressure formed behind the projectile's base. The investigation of the burning velocity was conducted by measuring the burning time of pyrotechnic charges pressed into aluminum tubes (height15 mm, radius 8 mm and wall thickness of 1 and 2 mm) using a "DUNKES" hydraulic press.

The mass of composition to be pressed into the aluminum tubes was measured on a digital balance with mg precision. The height of the aluminum tube represented the time measuring range. The combustion time measurements were performed using a VOD 811 system with specially adjusted software for the correct display of lower combustion velocities.

4 Results and Discussion

4.1 Influence of the binder percentage on the combustion velocity

The investigation conditions were:

- charge density 1.73 g/cm^3,
- chamber wall thickness 2 mm,
- neutral oxygen balance.

The portion of binder for lactose based mixtures was 3-7%, and for ascorbic acid based mixtures 3-6%. An ascorbic acid mixture with 7% binder was not prepared because the mashing phase was almost impossible.

Through analysis of the data in Table 2, it is obvious that an increase in the binder portion causes a decrease in the combustion velocity and the variation coefficient, due to better homogeneity of the mixture.

Table 2. Investigation of binder influence on the linear burning velocity

Composition label	Binder portion, mass [%]	ρ [g/cm^3]	Burning velocity, [mm/s]				BVav	Sd	VC
Lactose based compositions									
010/12	3	1.73	0.73	0.70	0.68	0.74	0.71	0.03	3.94
006/12	4		0.69	0.67	0.66	0.70	0.68	0.02	2.40
001/12	5		0.70	0.66	0.70	0.71	0.69	0.02	2.98
004/12	6		0.68	0.67	0.64	0.67	0.67	0.02	2.30
005/12	7		0.64	0.63	0.63	0.64	0.64	0.00	0.71
Ascorbic acid based compositions									
013/12	3	1.73	2.25	2.23	2.23	2.18	2.22	0.03	1.30
012/12	4		1.60	1.66	1.64	1.64	1.64	0.02	1.47
007/12	5		1.21	1.21	1.19	1.20	1.20	0.01	1.01
011/12	6		1.13	1.13	1.14	1.13	1.14	0.01	0.52

Bearing in mind that in all cases the variation coefficient was below 5, the compositions investigated could be regarded as very homogeneous. Nevertheless, small deviations from the expected values of the burning velocity and the variation coefficient are the result of mixture imperfections related to limitations in the mixture production technology. The values of the combustion velocity for lactose based mixtures with 4, 5 and 6 mass% of binder are very similar (0.68; 0.69; 0.67, respectively), so some deviations can be assigned to mixture imperfection, as already mentioned.

Further analysis of the data in Table 2 shows that when the binder portion is increased from 3 to 6 mass% for lactose based compositions, this leads to only a 5.63% decrease in the burning velocity, whilst ascorbic acid based mixtures caused a significantly greater decrease of 48.65%.

4.2 Influence of oxygen balance on the combustion velocity

The investigation conditions were:

- charge density 1.73 g/cm^3,
- chamber wall thickness 2 mm,
- 5% of binder.

The optimization of the pyrotechnic mixtures was done to give mixtures with positive, neutral and negative oxygen balances (OB). The combustion velocity investigation results are given in Table 3.

Table 3. Investigation of the influence of the oxygen balance on the linear burning velocity

Composition label	Oxygen balance, [%]	Burning velocity, [mm/s]				BVav	Sd	VK
Lactose based compositions								
001/12	-0.69	0.70	0.66	0.70	0.71	0.69	0.02	2.98
002/12	+15.24	0.69	0.71	0.69	0.69	0.70	0.01	1.56
003/12	-14.39	0.55	0.55	0.54	0.55	0.55	0.00	0.88
Ascorbic acid based compositions								
007/12	-0.46	1.21	1.21	1.19	1.20	1.20	0.01	1.01
008/12	+15.52	1.24	1.23	1.20	1.26	1.23	0.03	2.03
009/12	-14.26	1.28	1.27	1.26	1.28	1.27	0.01	0.93

Analysis of the data in Table 3 shows that ascorbic acid based mixtures exhibited only a 5.83% increase in combustion velocity, between compositions with neutral and positive OBs, which makes them almost immune to oxygen balance changes in the investigated range. That trend does not apply to lactose based mixtures, which had a decrease in combustion velocity of 21.4% in changing the OB from +15 to -14%.

4.3 Influence of charge density on the combustion velocity

The investigation conditions were:

- charge densities 1.73; 1.87 and 2.00 g/cm^3,
- chamber wall thickness 1 mm,
- all pyrotechnic mixtures (Table 1).

The investigation of the influence of charge density on the combustion velocity was performed on all of the mixtures presented in Table 1. Pyrotechnic charges with densities of 1.73, 1.87 and 2.00 g/cm^3 were pressed into aluminum tubes with 1 mm thick walls.

Whilst higher charge density values, in the case of metallic fuel based pyrotechnic charges, have a positive influence on heat transfer beneath the combustion zone, contributing to combustion stability and an increase in burning velocity, the same does not apply to organic based compositions. The investigation results show that an increase in charge density has a negative influence on the combustion velocity. For organic based compositions, higher charge densities decrease the combustion surface which consequently produces less heat for preheating layers beneath the combustion zone, thus decreasing the combustion velocity. The negative influence of an increase in charge density on the burning velocity is shown in Figures 1 and 2.

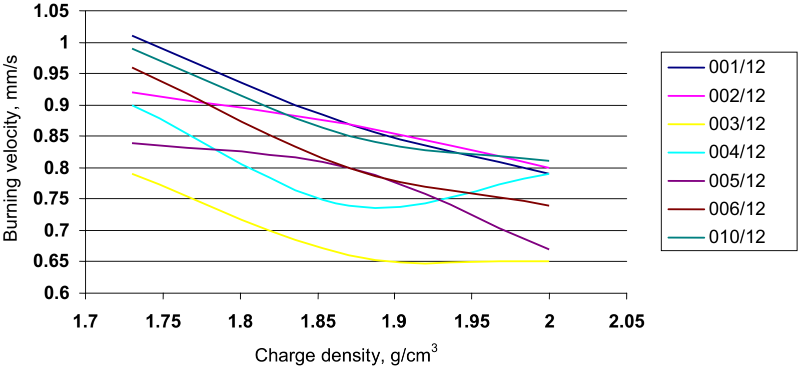

Figure 1. Influence of charge density lactose based compositions.

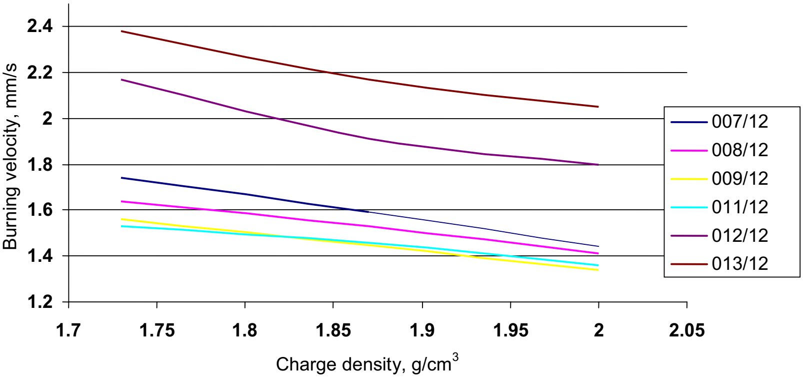

Figure 2. Influence of charge density ascorbic acid based compositions.

4.4 Influence of chamber wall thickness on the combustion velocity

The investigation conditions were:

- charge density 1.73 g/cm^3 for lactose based mixtures and 1.73; 1.87 and 2.00 g/cm^3 for ascorbic acid based mixtures,
- modified and standardized aluminum tubes,
- all pyrotechnic mixtures (Table 1).

Analysis of the results shows that the influence of the chamber wall thickness on the combustion velocity is very complex. The influence of the chamber wall thickness on the burning velocity is mostly related to heat transfer from the combustion zone to layers beneath that zone. Organic fuel based pyrotechnic mixtures are poor heat conductors unlike the metallic chamber walls. The better conductivity of the chamber walls helps in preheating the layers beneath the combustion zone from layers that are in contact with the chamber walls towards the charge center, but they also actively radiate heat to the surroundings, thus dissipating heat. An increase in the thickness of the chamber walls from 1 to 2 mm also increases the outer surface (from 3.71 to 5.04 cm^2) from which the chamber walls can radiate heat to the surroundings. The increase in the outer surface is 35.85%, whilst the inner surface, from which the chamber walls are heating charge layers beneath the combustion zone, remains unchanged (2.51 cm^2) (Figures 3 and 4).

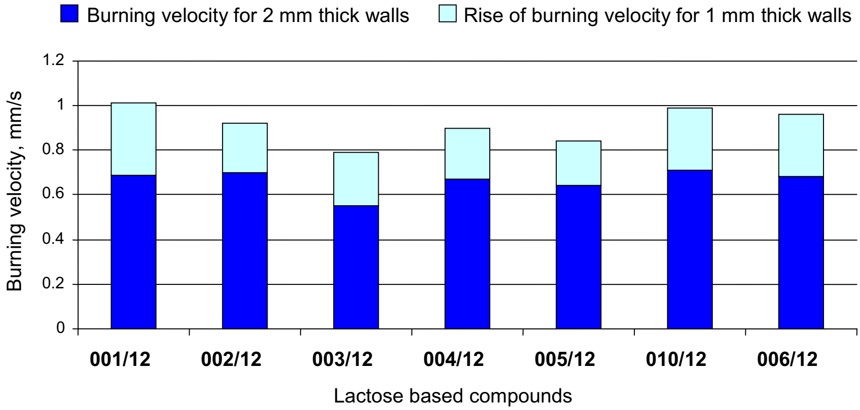

Figure 3. Influence of the chamber wall thickness on the burning velocity for lactose based compositions at 1.73 g/cm^3 charge density.

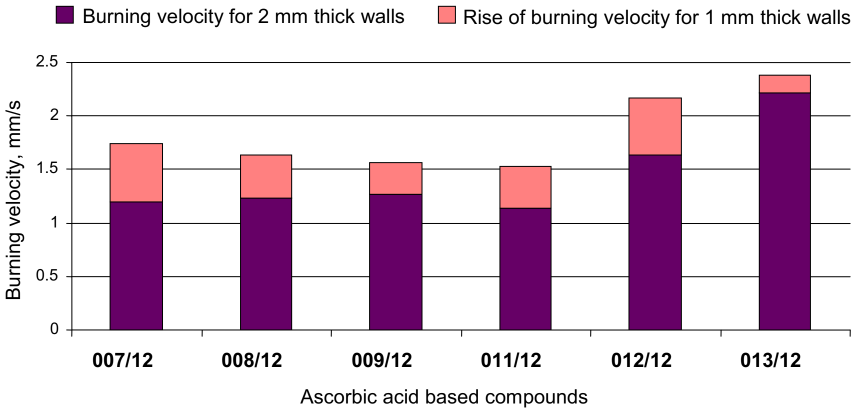

Figure 4. Influence of the chamber wall thickness on the burning velocity for ascorbic acid based compositions at 1.73 g/cm^3 charge density.

Figures 3 and 4 represent the differences between the burning velocities of pyrotechnic compositions pressed into modified and standardized aluminum tubes for lactose (Figure 3) and ascorbic acid (Figure 4) based compositions.

Bearing in mind that the gas generator chamber is inserted into the base of the projectile, and has intimate contact with it, dissipation of heat through the chamber walls, in a real case scenario, is additionally stimulated, especially for mixtures with poorer heat conductivity. The investigation results concur with this observation. The combustion velocity of mixtures pressed into the thinner walled tubes is higher than for thicker walled aluminum tubes. The influence of the chamber wall thickness on the combustion velocity for lactose based mixtures showed excellent consistency; minor deviations can be explained only through the simultaneous influence of several parameters, which will be referred to in the following section.

4.5 Multi parameter analysis

In the previous sections of this paper the isolated influence of each parameter of interest on the combustion velocity was discussed. In this section, however, an all-round perspective of the combined influence of several parameters on the combustion velocity will be analyzed. This is very important, because, only through meticulous analysis of the combustion process, can the behaviour of GG charges, under real-life usage conditions, be fairly predicted. It is a very complex procedure, because, in the equation that should depict the combustion process, some of the parameters need to be set at fixed values or to have a defined and predictable influence on the burning velocity, and thus enable the observation of the influence of other parameter-parameter interactions on the combustion process. The first step in this process will be to identify the parameter which showed the most consistent influence on the combustion velocity, to define that influence and in further analysis treat it as a constant. That chosen parameter was the chamber wall thickness.

Figures 5 and 6 present the increase in burning velocity as a result of the combined influence of the variation in the thickness of the chamber walls and the oxygen balance for lactose (Figure 5) and ascorbic acid (Figure 6) based pyrotechnic charges, with a charge density of 1.73 g/cm^3.

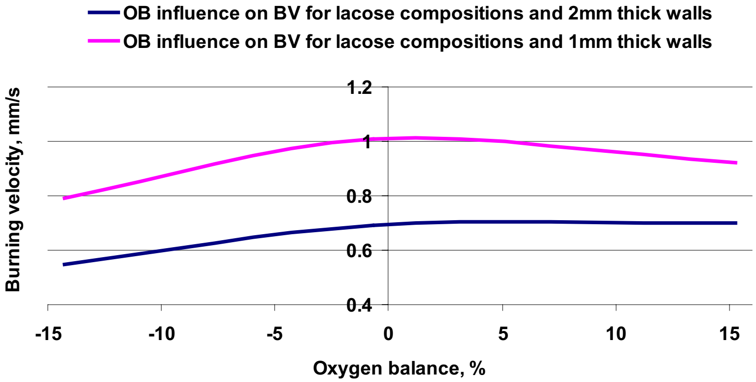

Figure 5. Combined influence of chamber wall thickness and OB on the burning velocity for lactose based compositions at 1.73 g/cm^3 charge density.

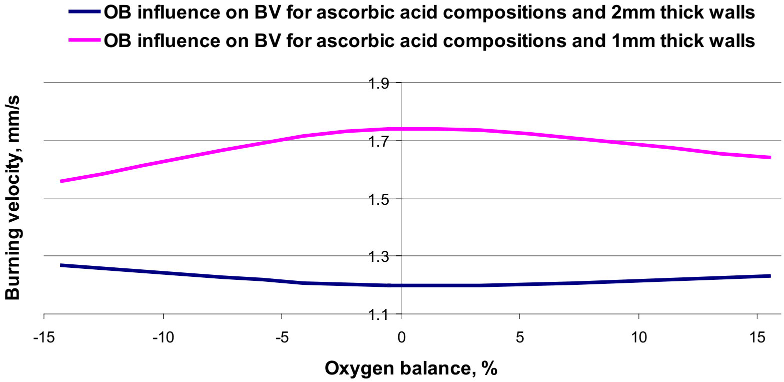

Figure 6. Combined influence of chamber wall thickness and OB on the burning velocity for ascorbic acid based compositions at 1.73 g/cm^3 charge density.

The highest increase in burning velocity was obtained with neutral oxygen balanced mixtures pressed into modified aluminum tubes for both lactose and ascorbic acid fuel based mixtures. That is because a neutral OB represents the mixture with an optimal component ratio, which yields the maximum heat output thorough the combustion process. All of that heat is available for transfer and preheats layers beneath the combustion zone, resulting in the increase in combustion velocity.

In Figure 5, we observe that the increase in combustion velocity for lactose based mixtures with a negative OB is almost identical to that for mixtures with a positive OB (0.22 and 0.24 mm/s, respectively). A slightly higher increase in the combustion velocity for mixtures with a neutral OB is related to the combined influence of the maximum heat output generated from a neutral OB and the favorable influence of thinner chamber walls on heat conduction.

Figure 6 is very interesting because it shows that for a neutral oxygen balanced mixture and thicker chamber walls, when the heat output from the combustion process is the greatest, a small collapse in the burning velocity is observed. Whilst for the thinner chamber wall and neutral oxygen balance, a significant increase in the burning velocity is observed. That abnormality could be explained by the fact that the significant heat output for neutral oxygen balanced mixtures is used more for heating the thicker, better heat-conductive chamber and heat dissipation to the surroundings than for preheating the less conductive pyrotechnic charge layers. Consequently, for thinner chamber walls less heat is needed for heating the chamber walls and more heat is available for preheating the pyrotechnic charge layers, leading to higher burning velocities.

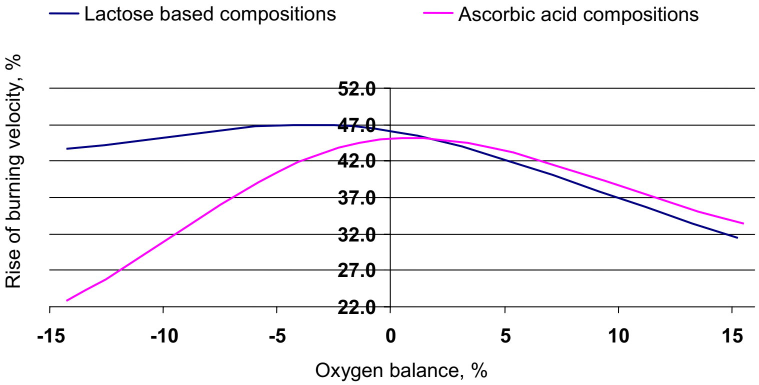

Figure 7. Influence of oxygen balance on the increase in burning velocity between 1 and 2 mm thick walls for both lactose and ascorbic acid based compositions at 1.73 g/cm^3 charge density.

The consistent positive influence of thinner chamber walls on the burning velocity of GG pyrotechnic charges is best presented on a comparative display of increase in burning velocity for modified aluminum tubes for both lactose and ascorbic acid based pyrotechnic charges with various OBs (Figure 7). The increase in burning velocity for each pyrotechnic composition in Figure 7 represents the difference between its burning velocity for different oxygen balances when pressed into modified and standardized aluminum tubes. Although we have noticed that both lactose and ascorbic acid based compositions have a maximum increase in burning velocity for neutral OBs, looking closely at Figure 7 one can also notice the different behaviour for positive and negative OBs.

Whilst the difference between the burning velocities for modified and standardized aluminum tubes (increase in burning velocity) of lactose based pyrotechnic charges is smaller for positive than for negative OBs, when analyzing the results for ascorbic acid compositions, the opposite trend is observed. The differences in behaviour for defined investigation conditions arise from differences in the nature of these two fuel components. In analyzing the lactose compositions, for example, the fact that lactose melts around 214 °C before it undergoes thermal degradation should be considered. Molten lactose has a positive influence on the thermal conductivity of the compositions, and therefore a negative OB (fuel richer mixture) exhibits a greater increase in burning velocity than a positive OB composition (fuel poorer).

In order to examine this statement, a comparative investigation of how different portions of the compositions' fuel components, pressed into modified and standardized aluminum tubes, influences the burning velocity, was conducted (these results are presented in Figure 8).

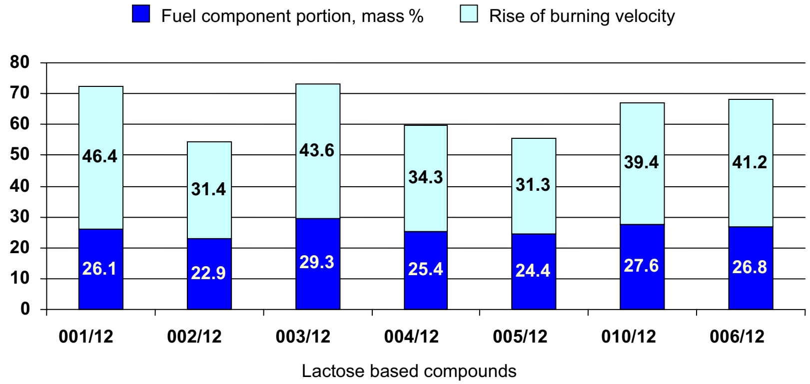

Figure 8. Combined influence of the fuel component portion and the chamber wall thickness on the burning velocity.

Analyzing the mixture fuel portions, from Table 1, and the differences in the burning velocity (Figure 8), it is clear that compositions with the highest increase in burning velocity have the highest portions of fuel component (001/12 and 003/12) and vice versa, the lowest increase in burning velocity being registered for compositions with the lowest fuel component (002/12 and 005/12). The behaviour of ascorbic acid based compositions is slightly different, because it lacks the same type of mixture component, ascorbic acid melts at the same temperature as it undergoes thermal degradation, around 525 °C. So, greater burning velocity differences, between compositions pressed into standardized and modified aluminum tubes, are registered for positive OBs (oxidizer richer). This is associated only with higher portions of the component that has better conducting characteristics (potassium perchlorate).

The influence of charge density, in combination with different thicknesses of the chamber walls and OBs, on the burning velocity was investigated for ascorbic acid compositions (these results are presented in Figures 9-11).

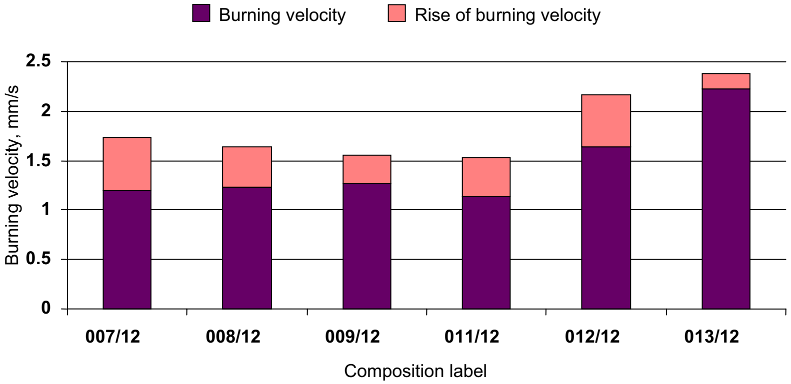

Figure 9. Combined influence of charge density, chamber wall thickness and OB on the burning velocity for charge density 1.73 g/cm^3.

From Figures 9, 10 and 11 it is clear that both the burning velocity and the increase in burning velocity, for compositions pressed into modified and standardized aluminum tubes, steadily decrease with increase in charge density. Also, in going from the lowest to the highest charge densities, unification of the burning velocity differences among all compositions is clear. This could be explained by an increase in the volumetric concentration of the component with the best conducting characteristics, potassium perchlorate, whose mass portion is very similar for all ascorbic based compositions, going from 62.5 to 69.1 mass%, along with a reduction in charge porosity, which has a negative influence on the burning velocity through a decrease in combustion surface.

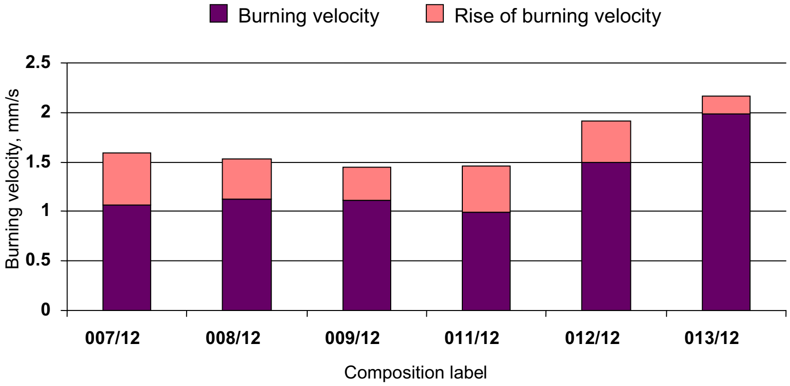

Figure 10. Combined influence of charge density, chamber wall thickness and OB on the burning velocity for charge density 1.87 g/cm^3.

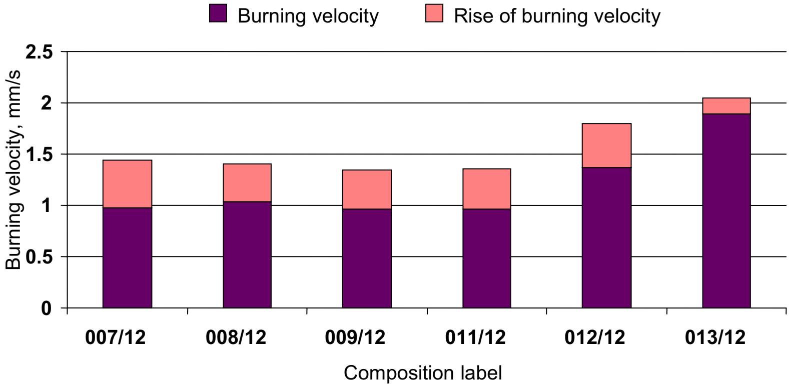

Figure 11. Combined influence of charge density, chamber wall thickness and OB on the burning velocity for charge density 2.00 g/cm^3.

5 Conclusions

An investigation of technological parameters which influences combustion velocity has shown that:

- An increase in the binder portion has a positive influence on mixture homogeneity and a negative influence on combustion velocity, which concurs with the common understanding that the binder acts as a retardant [4]. Because the VC (variation coefficient), as a criterion of data validity and mixture homogeneity has satisfactory values, less than 5%, for all of the investigated binder portions, the binder portion in the final composition should be defined in compliance with a desired combustion velocity.

- The oxygen balance (OB) has an opposite influence on the combustion velocity for lactose and ascorbic acid based compositions. Whilst lactose based compositions have a higher increase in burning velocity for negative OB than for positive OB (lactose, with a melting point around 200 °C, enhances the thermal conductivity) the opposite trend is observed for ascorbic based compositions. A desirable deviation from neutral OB is ± 5%, because higher deviations from a neutral OB lead to significant combustion velocity decreases.
- The thickness of the gas generator casing enhances the influence of other parameters and should be considered with utmost caution. Thicker casing walls require more heat for heating up to a certain temperature, as well as radiating more heat as a result of their greater outer surface area, from which they radiate energy to the surroundings. The results carried out with 1 and 2 mm thick aluminum tubes showed that with thinner walls, for the same composition and same charge densities, it is possible to get up to 45% higher values of the combustion velocity. Consequently, it is very important to isolate the gas generator casing from the rest of the projectiles base in which it is inserted, in order to prevent excess heat dissipation.
- Summing up all of the results of this investigation, we can confidently say that the highest increase in the combustion velocity would be obtained using organic based mixtures with OBs from -5 to +5%, binder portions between 4 and 6%, charge densities around 1.85 g/cm^3 and pressed into thin steel casings isolated with O-rings, or some other method, from the rest of the projectile's base.

6 References

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