EXPERIMENTAL STUDY REGARDING BURNING PROCESS SPECIFIC TO DIFFERENT TYPES OF PROPELLANTS BY MEANS OF CLOSED VESSEL TESTS

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The present work refers to the determination and characterization of the combustion laws specific to several gun and rocket propellants.

Our approach takes into account the combustion process when firing at two different densities in closed vessel. In the work procedure, the inherent phenomena were taken into account, namely, energy losses through heat transfer to the walls of the closed vessel, which affect the maximum pressure values.

The results showed that the experimental coefficient ν, that depends on the nature of the propellant and its burning conditions, cannot always be approximated with the unitary value, which is why the simplified models of internal ballistics do not apply to the case of these types of propellants.

Keywords: burning rate law, closed vessel, propellants, heat loss, pressure.

1. Introduction

Propellants are energetic materials that undergo an explosive transformation of the deflagration type, releasing in a short time a high amount of hot gases that can be used to launch projectiles or propel a rocket [1].

The study of the combustion of energetic materials plays an important role in the burning phenomenon. Due to the fact that the actual process is complex experimental tests are carried out to determine the combustion laws of the compositions as well as the formation of gases [2].

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The burning rate of propellants is represented based on various empirical formulas such as those of Vieille, Vucalov and Sébert. Moreover, some studies show that there are compositions, for which empirical coefficients differ depending on the pressure range at which combustion occurs. Also, the bibliography research indicates some inconsistency of the results regarding the experimental coefficients [2].

In 2001 Juhasz and Homan discovered that heat loss through the walls of the closed vessel is proportional to the volume to surface ratio using their XLCB data processing program. In the experimental tests carried out in the closed vessels with different volumes with identical propellants, the burn rate led to a difference of up to 3 % [3].

Khomenko and Shirokov’s method (2006) start by asserting that energy losses due to heat transfer can be assumed to be the difference between the total energy available in the propellant and the energy converted into gas pressure [4].

In other experiments carried out by Trebinski et al. in 2016, the measure to which loading densities can influence heat losses was evaluated. After the tests it was found that at high loading densities the heat losses had a reduced effect compared to the case of lower densities where the effect was more pronounced [5].

The aim of the paper is to determine and characterize the geometric law of combustion specific to different types of double-base propellants, also referred to as smokeless powders. The geometric law of combustion analyzes the phenomenon of combustion and allows taking into account the influence of the shape and dimensions of the powder elements on the burning rate at constant volume in the closed vessel. It was also calculated the burnt fraction, the constant and the experimental coefficient used in the burning rate expression.

2. Theoretical aspects

The mathematical model which describes the combustion phenomenon is based on the following considerations [6]:

- the elements that form the powder charge are strictly equal in size and homogeneous;
- the ignition of the powder elements occurs instantly;
- were taken into account the heat loss in the walls of the closed vessel, losses that will be discuss further in this paper.

The burning rate law refers to the dependence of the burning rate of propellants upon pressure, which is determined by processing the pressure curve as a function of time.

Equation (1) shows that the burning rate is proportional to the pressure raised to a power ν known as the experimental coefficient:

$$u = A \cdot p^{\nu} \quad (1)$$

Following many experiments and researches carried out in the closed vessel regarding the dependence between the maximum pressure and the charge density, the relationship for the maximum pressure was obtained:

$$p_{\max} = \frac{f\Delta}{1-\alpha\Delta} \quad (2)$$

where Δ represents the charge density and f, α constant coefficients.

Experimentally, based on the values of the maximum pressures obtained during several tests carried out in the closed vessel at different charge densities the powder strength and covolume can be determined [6].

Using equation (2) and the results obtained for two different charge densities, Δ_1 and Δ_2, the expressions of the two ballistic characteristics are obtained:

$$a = \frac{\frac{p_{\max 2}}{\Delta_2} - \frac{p_{\max 1}}{\Delta_1}}{p_{\max 2} - p_{\max 1}} \quad (3)$$

$$f = \frac{p_{\max 1}}{\Delta_1} - \alpha p_{\max 2} \quad (4)$$

After performing the calculations, can be determined the burnt fraction $\psi(p)$ as follows:

$$\psi = \frac{\frac{1}{\Delta} - \frac{1}{\delta}}{\frac{f}{p - p_a} + \alpha - \frac{1}{\delta}} \quad (5)$$

Determining the burning rate law according to the expression $u = A \cdot p^{\nu}$ involves the calculation on the basis of experimental data of two characteristics, a and ν. The burning area for the two tests is considered to have identical values for the same value of the fraction of powder burned [6].

The coefficient ν can be determined using the following expression:

$$\nu = \frac{\int_0^1 \ln\left(\frac{\psi_{\Delta 1}}{\psi_{\Delta 2}}\right) d\psi}{\int_0^1 \ln\left(\frac{p_{\Delta 1}}{p_{\Delta 2}}\right) d\psi} \quad (6)$$

Knowing ν can be calculated the constant A with the formula:

$$A = \frac{e_1}{\int_0^{t_{k2}} p_{\Delta 2}{}^{\nu} dt} \tag{7}$$

where A represents the experimental coefficient that depends on the nature of the propellant and its burning conditions.

When, in the calculations, the pressure given by the combustion of the primer is not neglected, p_a, and the combustion of the powder is considered to start once this value is reached, the integration from relation (7) starts from the corresponding time instant, t_a.

The thermal energy of the powder gases consumed by heating the walls of the vessel is called heat loss. This leads to the decrease of the maximum pressures as well as the current pressures compared to the situation where there would be no losses. Due to this fact, all quantities underlying the experimental curve p=f(t) will be modified [6].

In most cases, the assessment of heat losses is determined experimentally, due to the short duration of the powder combustion process in the manometric installation, the rapidity of the pressure variation and the difficulties related to determining the temperature variation of the gases and the vessel's wall [6].

To determine the pressure loss it is used the following equation:

$$\Delta p_{\max} = p_{\max} \cdot \frac{C_M}{0.7774} \cdot \frac{S_b}{W_0} \cdot \frac{1}{\Delta} \% \tag{8}$$

where $p_{\max}$ is the maximum pressure obtained, C_M represents the quantity corresponding to the combustion time extracted using the Muraour curve, S_b is the inside surface of the closed vessel, W_0 the volume of the vessel and Δ represents charge density [6].

C_M depends on the nature of the propellant and the total burning time which is influenced by the thickness of the propellant.

Following the evaluation of the losses through heat transfer, the relative correction is performed on the basis of which the new curve p=f(t) is drawn using the formula [6]:

$$p_{iact} = p_i \cdot \left(1 + \frac{\Delta p_{\max}}{p_{\max} - p_a}\right) \tag{9}$$

3. Experimental research

Experimental tests were carried out using two types of double-based propellants at different loading densities, respectively 150 $\frac{kg}{m^3}$ and 200 $\frac{kg}{m^3}$ in order to make a more relevant comparison and analysis. These propellants contain nitroglycerine (NG) in addition to nitrocellulose (NC) and is considered to be more energetic than single-base propellants.

The device with which the experimental tests can be carried out is called a closed vessel (Fig. 1). With this device, it is possible to obtain the variation of the pressure of the gases formed, inside the combustion chamber, as a function of time p=f(t).

Fig.1. Component parts of the closed vessel
(1-main body, 2- piezo-electric transducer, 3- exhaust gas device (valve), 4- ignition bolt)

Fig. 2 show DP-1 and DP-2 propellants used in closed vessel experiments. There are different types of propellants like flake, ball, cord, single perf (tubular), ellipsoid [7].

In this case the form used is ribbon propellant cut into small equal pieces to have a suitable density, as it can be seen in Fig. 2.

The notations used are distinct and do not denote the particular characteristics of each powder for its identification.

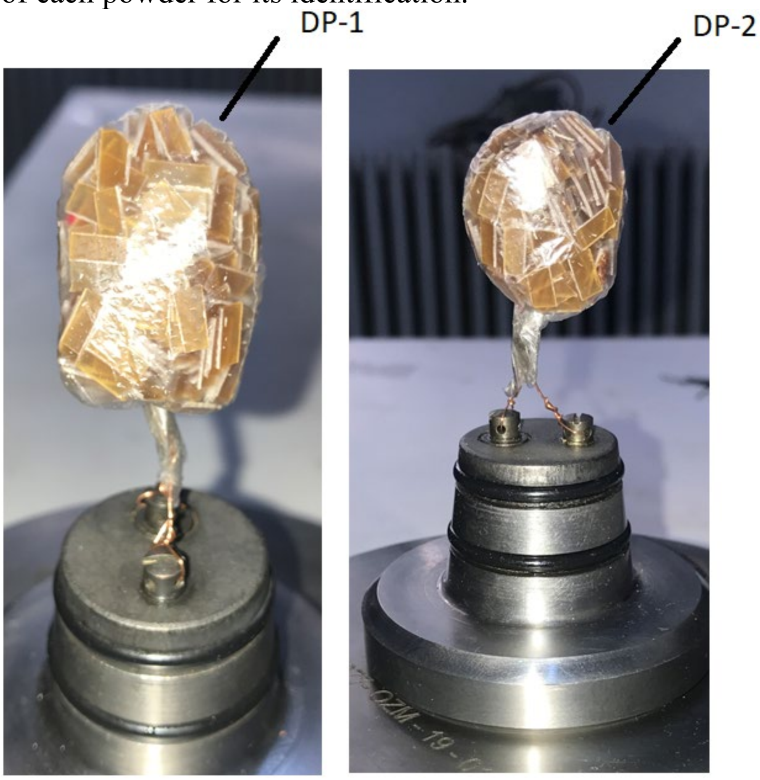

Fig.2. Propellants used in experiments

4. Results

Burning each explosive composition provide results in the form of the p=f(t) profile. The following figures highlight the differences on the pressure graph depending on the amounts of compositions used from each type of powder.

Within the figure bellow there are presented in a comparative manner results of closed vessel pressure vs. time for prediction models and experimental test. It can be observed that burning times increase depending on the thickness of the powder elements and decrease depending on the density of the explosive charge.

Fig. 3 shows the evolution of pressures in relation to time for the two types of propellants, DP-1 and DP-2, at two different loading densities. During the closed vessel's experiments carried out at a loading density of 150 $\frac{kg}{m^3}$, the maximum pressure value was approximately $1.8 \cdot 10^8$ Pa for both types of propellants used, but it can be observed that the DP-1 propellant is more vivacious than the DP-2 propellant, reaching the maximum value of pressure faster. The same case is also observed for the experiments performed at the loading density of 200 $\frac{kg}{m^3}$, where the maximum pressure obtained is approximately $2.6 \cdot 10^8$ Pa.

This happens due to the geometry of the lamellar propellant elements DP-1 which have a smaller width than DP-2.

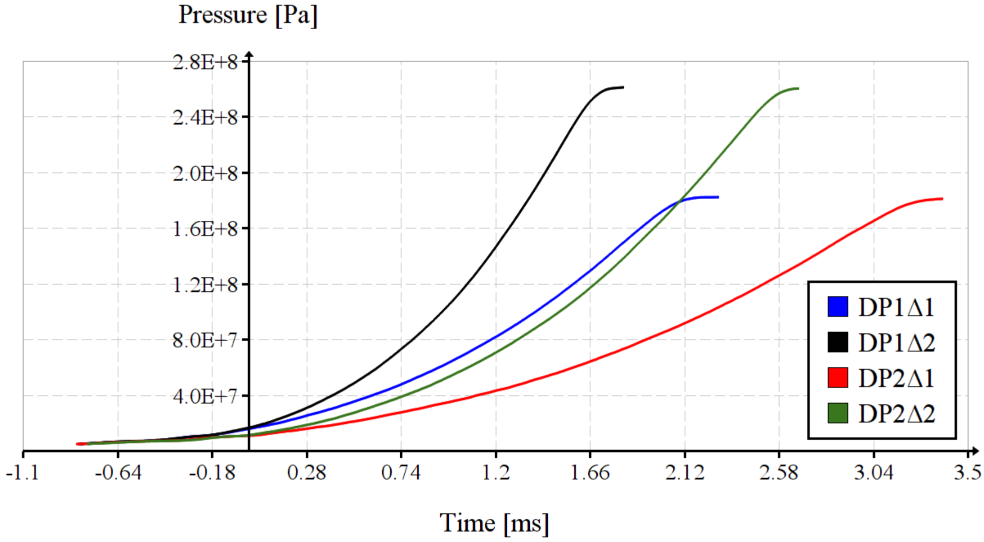

Fig.3. Pressures of the propellants used in experiments depending on the burning time

In the next table it is displayed the data of the burning time and the maximum pressure corresponding to the two types of propellants used in the experimental tests at two different densities $\Delta_1 = 150 \frac{kg}{m^3}$ and $\Delta_2 = 200 \frac{kg}{m^3}$.

Table 1

Data details regarding two types of propellants depending on two different charge densities

	DP-1		DP-2	
	Δ_1	Δ_2	Δ_1	Δ_2
Burn time [ms]	5.18	4.43	6.58	6.53
Maximum pressure [Pa]	$1.824 \cdot 10^8$	$2.613 \cdot 10^8$	$1.812 \cdot 10^8$	$2.604 \cdot 10^8$

In Fig.4, the pressure graph corresponding to the DP-2 propellant shows the decrease of the maximum pressure along with the current pressures compared to the situation in which there would be no heat loss. Due to this fact, all quantities underlying the experimental curve p=f(t) will be modified.

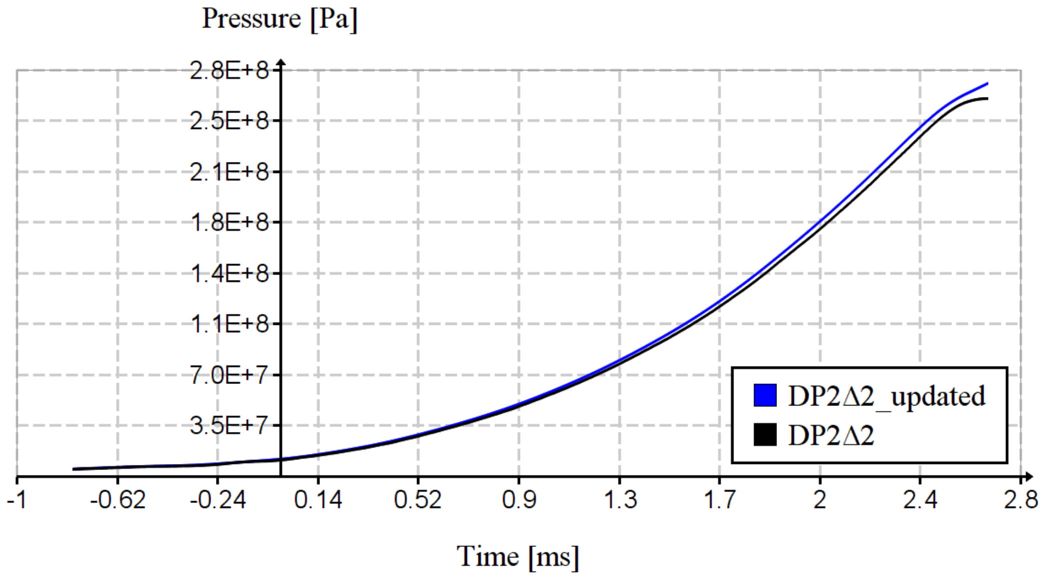

Fig. 4. The differences between the pressures taking into account the heat losses

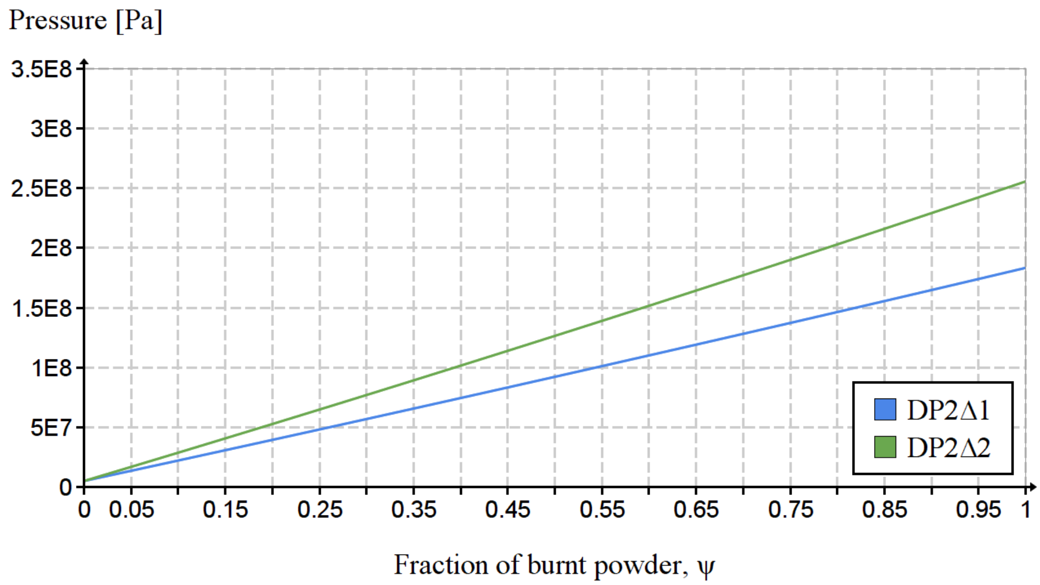

Fig.5. The pressures corresponding to the two charge densities depending on the fraction of burnt powder

In Fig. 5 it is observed the evolution of the pressures corresponding to the two different charge densities depending on the fraction of burnt powder chosen common for a comparative analysis as close as possible to the truth. In addition, it can also be noticed that both pressures start from the primer pressure value of 50 bar and stop at the moment when the fraction of burnt powder has the value of 1, the moment that corresponds to the end of the propellant's burning.

5. Conclusions

The results of the experimental tests carried out in the closed vessel demonstrated the effectiveness of the method to determine and study the ballistic parameters of the propellants. The advantage of using the closed vessel consists in the fact that can be loaded a small amount of charge that can be initiated with complete safety and the process can be repeated in short time to obtain comparative data.

After investigating the combustion process of propellants of different shapes and densities, it is determined the strength and covolume of each type of propellant, taking into account the necessary temperature corrections due to energy losses through heat transfer to the walls of the closed vessel.

The experimental results obtained from tests confirm the Trebinski experiments because of the heat losses which had a significant effect when it was used lower charge densities.

The calculations performed to determine heat losses helped to understand the distribution of energy losses due to different factors. Determining the optimum parameters for the manometric configuration by solving the equations discussed in the theoretical part will help in better understanding of the phenomenon of propellant burning in closed vessel and improve the accuracy determination of energy losses.

The theoretical results obtained using numerical calculations were compared to the experimental data, being in good accord with the experimental results. This method is a very useful tool for designing new propellant charge, also providing the variation of temperature, burning area, burning fraction, etc. depending on time and thickness of burning.

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