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Investigations of Ballistic Characteristics of N340 Propellant

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Abstract. Results of investigations of ballistic characteristics of the single-based N340 propellant are presented. A novel approach, proposed in an earlier authors' work, was applied. Basing on pressure records, obtained in closed vessel tests the burning law and the dynamic vivacity function were determined. High value of the exponent in the burning law was obtained (1.25). This effect can be attributed to the process of infiltration of hot gases into propellant pores, enhanced by the increase in the pressure. The dynamic vivacity function was proved to be dependent on the value of the loading density. A simple analytical approximation of the averaged vivacity function was proposed. It describes the ballistic properties of the propellant much better than the geometric law of combustion. An effect of heat losses on the vivacity function was estimated, showing relatively small influence of the losses on the vivacity function. The obtained results confirmed applicability of the novel approach to the characterization of ballistic properties of fined-grained propellants.
Keywords: ballistic characteristics, single-based propellant, dynamic vivacity, burning law, heat losses

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1. INTRODUCTION

N340 single-based propellant is a propellant used in small caliber guns. It has high burning rate due to relatively large porosity (appr. 15%). This feature of the propellant makes it difficult to characterize its ballistic properties by the standard methods described in the STANAG 4115 [1]. In particular, the form function, determined on the basis of the geometry of propellant grains, does not give realistic assessment of the burning rate. Alternative approach to the use of the form function is determining the dynamic vivacity curve [2-4]. Such an approach to the characterization of ballistic properties of fine-grained propellants was used in [5].

There is no one widely accepted definition of the dynamic vivacity Γ. Its various definitions were analyzed in [6]. In the Report [7] it was defined as the ratio of the pressure time derivative to the product of the pressure and the maximum pressure.

In this paper, the definition of the dynamic vivacity was derived from the so-called "physical law of combustion", introduced in [2]. This law represents the mass burning rate of a propellant as a product of Γ function, depending on the chemical composition and the geometry of propellant grains, and a function of pressure, that takes into account the influence of pressure on the processes taking part inside the flame. The Γ function has been accepted in this paper as the dynamic vivacity.

In this paper the dynamic vivacity curves for N340 propellant are determined on the basis of results of the closed vessel tests. A procedure used for determining the vivacity includes determining the value of the exponent in the burning law and an assessment of the influence of heat losses. The procedure is described in details in [8]. It is briefly presented in the Chapter 2. The obtained results are presented and discussed in the Chapter 3. Main results are summed up in the Chapter 4.

2. MATERIALS AND METHODS

2.1. Experimental tests

N340 propellant manufactured by VIHTAUORI (Finland) was investigated. It is a single-based propellant in the form of cylindrical, single perforated grains. Nominal sizes of the grains are: length 1.1 mm, outer diameter 0.8 mm, the web 0.15 mm. The propellant material density is equal to 1330 kg/m^3.

Closed vessel tests were performed in 200 cm^3 capacity vessel for the following values of the loading density: Δ = 50, 75, 100, 125, 150, 175 kg/m^3. For each value of the loading density the test was repeated three times.

The propellant burning was initiated by a black powder igniter. The mass of the igniter was chosen, so as 3 MPa ignition pressure is attained.

The pressure inside the vessel was measured by 8QP 10 000 piezoelectric sensor manufactured by AVL List GmbH (Austria). Pressure courses were sampled with a time step equal to 25 μs for Δ = 50, 75, 100, 125 kg/m^3, 20 μs for Δ = 150 kg/m^3 and 10 μs for Δ = 175 kg/m^3.

2.2. Method of determining the dynamic vivacity function

In the first step of the analysis, parameters of the equation of state are determined. A simple form of the virial equation of state was chosen:

$$pv = nRT\left(1+\frac{\beta}{v}\right) \tag{1}$$

Here p means the pressure, v is the specific volume, n is the number of moles, R is the universal gas constant, T is the temperature, and β is the first virial coefficient. As it was shown in [9], this equation gives comparative results to the Noble-Abel equation of state in the pressure range used in closed vessel tests and provides a better approximation of results of thermochemical calculations for much higher pressures.

Assuming that during burning of the propellant the temperature is equal to the adiabatic temperature of flames T_b, we can represent Eq. (1) in the form:

$$pv = F + \frac{C}{v}, \quad F = nRT_b, \quad C = F\beta \tag{2}$$

For the end of the burning process v = 1/Δ. So we obtain the following relation between the maximum pressure p_{max} and the loading density:

$$\frac{p_{max}}{\Delta} = F + C\Delta, \quad \beta = \frac{C}{F} \tag{3}$$

Basing on this relation we can determine the values of the parameters F and β by using the values of p_{max} obtained for different values of the loading density. The dynamic vivacity Γ is defined by the formula:

$$\Gamma(\psi) = \frac{\frac{d\psi}{dt}}{f_b(p)} \tag{4}$$

Here ψ means the relative mass of the burned propellant.

The function $f_b(p)$ determining the burning law is assumed in the form:

$$f_b\left(p\right) = p_0 x^{\alpha}, \quad x = \frac{p}{p_0} \tag{5}$$

Here p_0 means the ambient pressure. In order to determine the vivacity values, the relative mass of the burned propellant ψ and the mass rate of burning dψ/dt should be calculated. The value of ψ is calculated by the formula:

$$p_s = p - p_z, \quad v = \frac{F + \sqrt{F^2 + 4 p_s C}}{2 p_s}, \quad \psi = \frac{\dfrac{\delta}{\Delta} - 1}{\delta v - 1} \tag{6}$$

The time derivative of ψ is calculated by the use of the formula:

$$\frac{d\psi}{dt} = \left(\frac{dp}{d\psi}\right)^{-1} \frac{dp}{dt}, \quad \frac{dp}{d\psi} = \frac{F}{v^2 \psi^2}\left(1 + \frac{2\beta}{v}\right)\left(\frac{1}{\Delta} - \frac{1}{\delta}\right) \tag{7}$$

In order to calculate dp/dt the experimental $p(t)$ curve is approximated by the cubic spline [10]. The approximation smooths the experimental curve.

In order to determine the value of the exponent α we can use the following relation, that can be derived from the definition of the dynamic vivacity Eq. (4) and the burning law Eq. (5):

$$w(\psi, x) = \log \frac{d\psi}{dt} = \log\left[p_0 \Gamma\left(\psi\right)\right] + \alpha \log x, \quad x = \frac{p}{p_0} \tag{8}$$

For a given value of ψ the function w is a linear function of log x. Determining the slope of this line we can find the value of the exponent α.

2.3. Calculation of heat losses

In order to determine the influence of heat losses on the dynamic vivacity the following differential equation is used:

$$\frac{d\psi}{dt} = \frac{\dfrac{\psi v^2}{v+\beta}\dfrac{dp}{dt} + \dfrac{1}{t_h}\left(\dfrac{p v^2}{v+\beta} - F\dfrac{T_w}{T_b}\right)}{F - \dfrac{pv}{v+\beta}\left[v - \dfrac{v+2\beta}{v+\beta}\dfrac{1}{\psi}\left(\dfrac{1}{\Delta} - \dfrac{1}{\delta}\right)\right]} \tag{9}$$

Here t_h means the characteristic time of heat losses, T_w means the temperature of the wall of the vessel.

The value of T_w is determined in an approximate way by using the formula:

$$T_w = \frac{TK\sqrt{t} + T_0}{K\sqrt{t} + 1}, \quad K = \frac{h\sqrt{a_C}}{\lambda} \tag{10}$$

Here T_0 means the initial temperature of the vessel wall, h is the coefficient of the heat exchange, a_C and λ mean respectively the thermal diffusivity and the heat conduction coefficient of the wall material. The temperature T is calculated by the use of the formula:

$$T = \frac{pvT_b}{F\left(1 + \frac{\beta}{v}\right)} \tag{11}$$

Equation 9 is derived in [8]. For solving it, we need the values of t_h and h. These values are estimated on the basis of analysis of descending parts of $p(t)$ curves. They can be approximated by the exponential decay formula:

$$p = p_f \exp\left(-\frac{t - t_f}{t_r}\right) \tag{12}$$

Here p_f means the value of pressure at the moment of the end of burning of the propellant t_f. It is somewhat smaller than p_{max} because attaining the maximum pressure does not correspond to the moment of the end of burning but to the moment when heat production is balanced by the heat losses. The time constant t_r can be determined from the relation:

$$\ln\frac{p_f}{p} = \frac{t - t_f}{t_r} \tag{13}$$

by using the linear regression. It is related to the time constant of the piezoelectric transducer discharge t_q and the heat losses time constant t_h:

$$\frac{1}{t_r} = \frac{1}{t_q} + \frac{1}{t_h} \tag{14}$$

It was shown in [8] that the heat losses time constant is proportional to the loading density:

$$t_h = \frac{\Delta QV}{\left(T_1 - T_{in}\right)Ah} \tag{15}$$

Here Q means the heat effect of the propellant, V is the vessel capacity and A is the area of its inner surface.

Relation (14) can be expressed in the form:

$$\frac{1}{t_r} = \frac{1}{t_q} + \frac{B}{\Delta}, \quad B = \frac{(T_1 - T_{in}) Ah}{QV} \tag{16}$$

Plotting the values of $1/t_r$ versus $1/\Delta$ and using the linear regression we can determine the values of t_q and B. Having determined the value of B we can calculate a value of the heat exchange coefficient h and the values of $t_h = B\Delta$.

3. RESULTS AND DISCUSSION

An exemplary $p(t)$ curve is shown in Fig. 1. The ascending part of it is used for determining the dynamic vivacity function, while the descending part is used for determining the heat exchange coefficient.

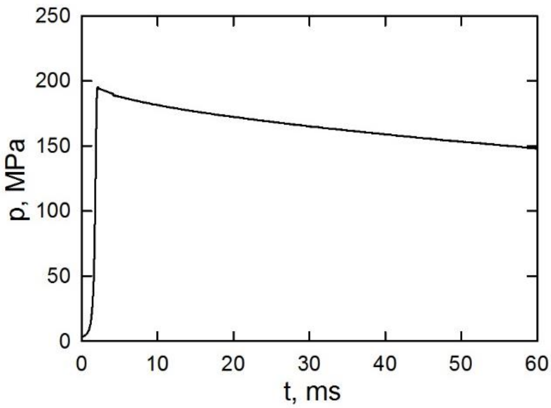

Fig. 1. An exemplifying $p(t)$ curve for the loading density 150 kg/m^3

Figure 2 shows relation between the experimental values of p_{max}/Δ and Δ. Error bars correspond to the 0.95 confidence level. The values of p_{max} were corrected by subtracting the value of the ignition pressure p_z. The values F = 1.032 MJ/kg and $\beta = 1.585$ m^3/Mg were determined by the linear regression.

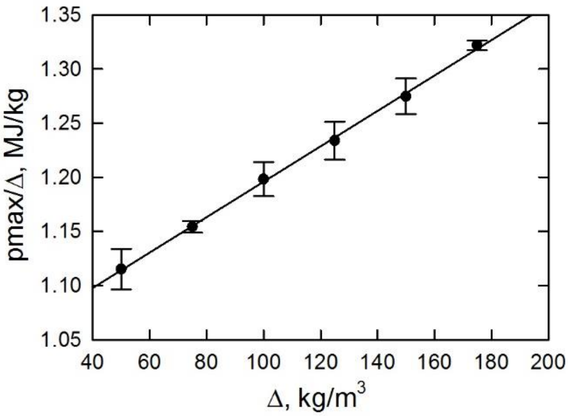

Fig. 2. Experimentally determined values of p_{max}/Δ and the regression line

Figure 3 presents dependence of the burning mass rate logarithm on the logarithm of relative pressure for constant values of ψ. Approximating this dependence by straight lines we can determine the value of the exponent α in accordance with the Eq. (8).

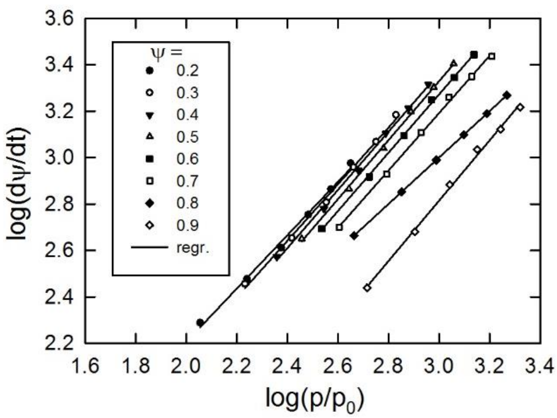

Fig. 3. Dependence of the logarithm of the burning mass rate on the logarithm of relative pressure for constant values of ψ

Figure 4 presents the results of determining the value of α for the given values of ψ. There is no unique value of α. The same effect was observed in [8] at the analysis of closed vessel tests data for the single-based propellant 5/7 NA. This effect was attributed in [8] to the dependence of the dynamic vivacity on the loading density. For different values of the loading density, the ignition process runs in various ways, influencing the whole process of the burning.

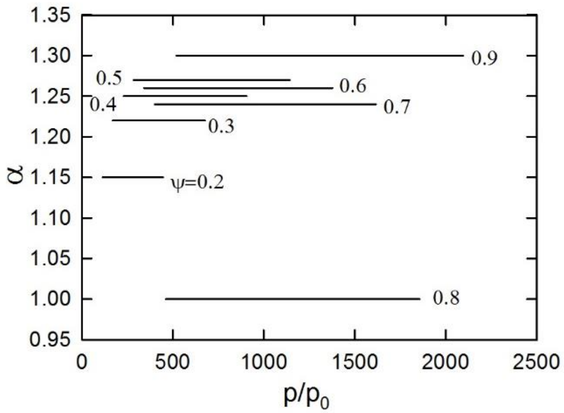

Fig. 4. Calculated values of the exponent α

The effect of the ignition process is especially pronounced for the initial stage of the burning process and its final stage. Therefore, for determining the value of the exponent α it is recommendable to use its values determined for the intermediate values of ψ. Similarly like in [8] an average value of α for the range $\psi \in [0.3,0.7]$ was calculated. It is equal to 1.25.

For comparison, in [8] for the single-based propellant 5/7 NA the value 0.925 was determined by using the same method. The high value of the exponent can be attributed to the infiltration of propellant gases into the pores of propellant grains. This process is enhanced by the increase in pressure, giving as a result very strong dependence of the burning rate on the pressure. Dynamic vivacity curves, calculated for α = 1.25, are shown in Fig. 5.

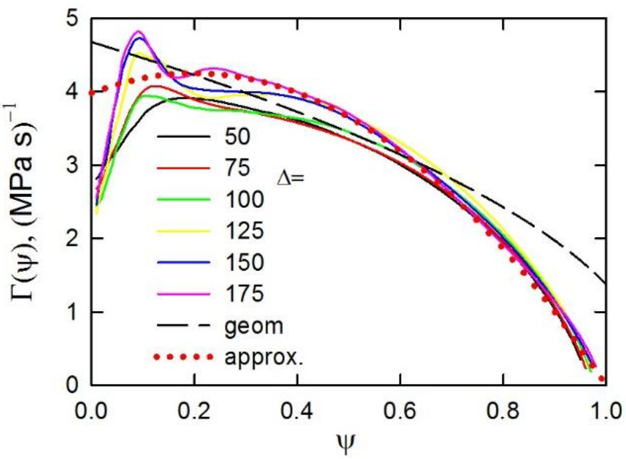

Fig. 5. Averaged dynamic vivacity curves for various loading densities; dashed line corresponds to the geometric law of burning; red points is the approximation (25)

For a given value of the loading density they represent an average dynamic vivacity curve for three tests.

The dynamic vivacity curves differ for various values of the loading density. They are compared with the dynamic vivacity curve determined on the basis of the geometric law (dashed line in Fig. 5). A form function, derived for the shape and sizes of the propellant grains, was used. The burning rate was determined for the pressure – time curves for the loading density 175 kg/m^3. It is a fairly good approximation of the dynamic vivacity curves for the range $\psi \in [0.1, 0.7]$. Let us try to approximate $\Gamma(\psi)$ curves by an analytical expression:

$$\Gamma_a(\psi) = \Gamma_0 \sigma(\psi) \tag{17}$$

The character of $\Gamma(\psi)$ curves suggests that:

$$\sigma(1) = 0 \tag{18}$$

Let us assume:

$$\sigma(0) = 1 \tag{19}$$

We approximate $\sigma(\psi)$ function by the second order polynomial:

$$\sigma(\psi) = a(1-\psi) + b(1-\psi)^2 \tag{20}$$

From Eq. (19) we have:

$$1 = a + b \tag{21}$$

Thus:

$$\sigma(\psi) = (1-\psi)\left[a + (1-a)(1-\psi)\right] \tag{22}$$

The value of a can be calculated by assuming the value of ψ for which $\Gamma(\psi)$ curve has a maximum:

$$\frac{d\sigma}{d\psi} = (1-2\psi)a - 2(1-\psi) = 0 \tag{23}$$

$$a = \frac{2(1-\psi_m)}{1-2\psi_m} \tag{24}$$

Assuming $\psi_m = 0.2$, we obtain a = 2.67. The value of Γ_0 is calculated by taking the value $\Gamma(0.2)$ = 4.25 (MPa s)$^{-1}$ for the loading density 175 kg/m^3 and dividing it by $\sigma(0.2)$.

Finally, we approximate $\Gamma(\psi)$ by the curve:

$$\Gamma_a(\psi) = 3.98(1-\psi)\left[2.67-1.67(1-\psi)\right] \tag{25}$$

The approximation, Eq. (25), is represented in Fig. 5 by the red dotted line. It is a very good approximation of the $\Gamma(\psi)$ curve for Δ = 175 kg/m^3 and $\psi > 0.15$.

Figure 6 presents dependence of the reciprocal of the time constant t_r on the reciprocal of the loading density. The values of $1/t_r$ have a very large scatter. Using Fisher – Snedecor significance test for the dependence of the values of t_r on Δ give the level of significance equal to 0.4. It means that the random disturbances completely mask the dependence of the time constant t_r on the loading density. In this situation we assume the average value t_r = 195 ms and we neglect t_q, that is expected to be much larger than t_r. It means that we assume the constant value t_h = 195 ms. For calculation of the values of the heat exchange coefficient we use the following data in the Eq. (15): V/A = 0.01 m, Q = 4.06 MJ/kg, T_b = 2850 K, T_0 = 300 K. Table 1 contains calculated values of the heat exchange coefficient h.

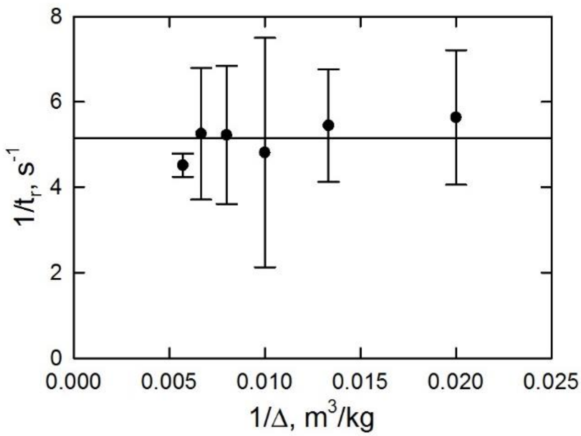

Fig. 6. Dependence of the reciprocal of the time constant t_r on the reciprocal of the loading density

Table 1. Calculated values of the heat exchange coefficient

Δ, kg/m^3	50	75	100	125	150	175
h, kJ/(m^{2}sK)	4.1	6.1	8.2	10.2	12.2	14.3

The following values of the heat conduction coefficient λ = 70 W/(mK) and the thermal diffusivity $a_c = 1.8 \times 10^{-5}$ m^2/s were taken.

Figures 7 and 8 show calculated dynamic vivacity curves for $\Delta = 50$ kg/m^3 and 175 kg/m^3. As it can be seen, the heat losses do not influence much the dynamic vivacity function. Their effects on the $\Gamma(\psi)$ curves are smaller than the influence of the loading density. Therefore, they can be neglected.

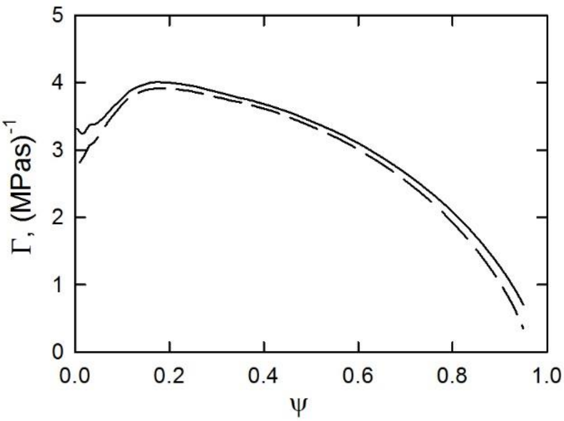

Fig. 7. Averaged dynamic vivacity curves for the loading density 50 kg/m^3: solid line – heat losses are taken into account, dashed line – without taking into account heat losses

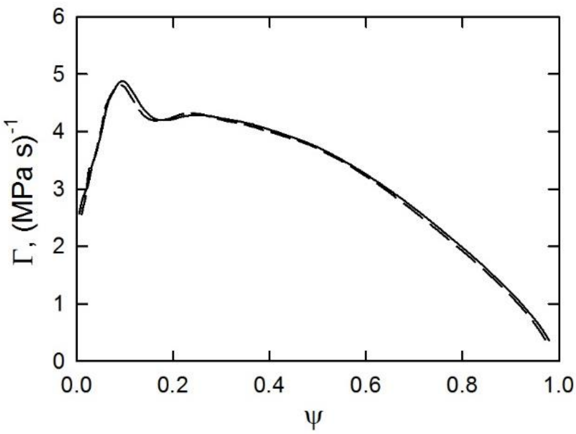

Fig. 8. Averaged dynamic vivacity curves for the loading density 175 kg/m^3: solid line – with taking into account heat losses, dashed line – without taking into account heat losses

4. CONCLUSIONS

Results of investigations of the ballistic characteristics of N340 propellant lead to the following conclusions:

1. The novel approach to the characterization of ballistic properties of fine-grained propellants, proposed in [8], proved to be applicable to the very fine and porous propellant.
2. Energetic effect of the propellant burning is characterized by the force constant equal to 1.032 MJ/kg and the first virial coefficient equal to 1.585 m^3/Mg.
3. The analysis did not give a unique value of the exponent in the burning law. Its average value is close to 1.25. Such a high value can be attributed to the infiltration of hot gases into pores, that is enhanced by the increase of pressure.
4. Dynamic vivacity curves of the propellant depend on the loading density. This dependence can be attributed to the differences in the ignition process for different loading densities.
5. An approximation of the experimental dynamic vivacity curves can be proposed that describes better the ballistic properties of the propellant than the form function based on the geometric law of burning.
6. Estimated influence of the heat losses on the dynamic vivacity is relatively small and it can be neglected.

In further investigations it is planned to use the ballistic characteristics of N340 propellant, determined in this work, in modelling of the internal ballistics cycle of a small gun and comparing results with experimental measurements.

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Badanie charakterystyk balistycznych prochu N340

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Streszczenie. Przedstawiono wyniki badań charakterystyk balistycznych jednobazowego prochu N340. Zastosowano nowe podejście, zaproponowane we wcześniejszej pracy autorów. Opierając się na przebiegach ciśnienia zmierzonych w próbach pirostatycznych, określono prawo spalania i dynamiczną żywość prochu. Uzyskano wysokie wartości wykładnika w prawie spalania (1.25). Efekt ten przypisano procesowi infiltracji gorących gazów do porów prochu, wzmocnionemu przez wzrost ciśnienia. Funkcja dynamicznej żywości okazała się zależna od gęstości ładowania. Zaproponowano prostą analityczną aproksymację funkcji żywości. Opisuje ona balistyczne właściwości prochu znacznie lepiej niż geometryczne prawo spalania. Dokonano oceny wpływu strat cieplnych na funkcję dynamicznej żywości, wykazując względnie mały wpływ strat cieplnych na funkcję żywości. Otrzymane rezultaty potwierdziły przydatność nowego podejścia do charakterystyki balistycznych właściwości prochów drobnoziarnistych.

Słowa kluczowe: charakterystyki balistyczne, proch jednobazowy, żywość dynamiczna, prawo spalania, straty cieplne