



Determination of Black Powder Burning Rate

P. Konečný^{1*} and Z. Křížan¹

¹ Department of Aerospace and Rocket Technology, University of Defence, Brno, Czech Republic

The manuscript was received on 28 May 2008 and was accepted after revision for publication on 18 September 2008.

Abstract:

The paper is focused on a method of experimental black powder burning law finding. This method issues from records acquired during black powder charge burning tests in closed vessel (ballistic bomb). Evaluation of data sets brings courses of parameters needed for calculation of instantaneous values of black powder burning rate. The burning law is then given as spare regression function of experimental data.

Keywords:

Black powder, burning law, internal ballistics

1. Introduction

The black powder is still used for igniters of smaller rocket motors and barrel weapon cartridges. The burning rate of black powder depends on a pressure similarly as in case of the solid propellant burning law. The igniting pressure in the solid propellant rocket motor reaches maximally two third of presupposed equilibrium working pressure in combustion chamber.

In the past, the black powder burning laws were obtained experimentally [1], [2]. Technical and measurement facilities for rocket motor testing did not allow recording of processes occurring during several thousandth of second with available accuracy at that time. At present time the modern data acquisition systems connected with PC enable to obtain very precise records of measured values that can be processed instantaneously in proper software and necessary physical values can be evaluated from them.

* Corresponding author: Department of Aerospace and Rocket Technology, University of Defence, Kounicova 65, CZ-612 00 Brno, Czech Republic, phone: +420 973 445 147, fax: +420 973 445 147, e-mail Pavel.Konecny@unob.cz

2. Black Powder Burning Test in Closed Vessel

The closed vessel test (ballistic bomb) is often used for finding out of black powder burning law. Selected weight of black powder charge is ignited in constant volume without the gas exhaust. The pressure inside the closed vessel course is measured and recorded. The values needed for the black powder burning rate determination are obtained from the pressure course record.

The black powder charge has not all grains in the same shape and dimensions. The shape for solution has to be simplified to the known simple geometric body, for example sphere or cylinder. Its dimensions are used as average ones for all grains of the selected black powder charge. The black powder is sifted through the system of sieves and the distribution of grains dimensions along the selected dimension range is assumed uniform. The initial web thickness is given as the average value of densities of two sieves which are used at the black powder sifting.

The burning of the black powder charge of given weight m_p in the constant volume of ballistic bomb is considered simply isotherm for the condition of burning rate and shape function determination. The general form of the pressure course is introduced in Fig. 1. The burning of black powder charge is usually divided into the three phases [1]:

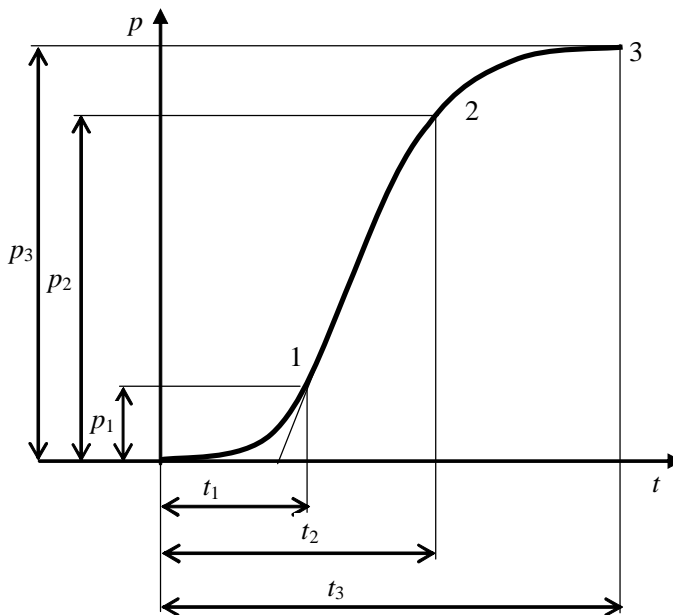


Fig.1 Pressure course of the black powder charge burning in closed vessel.

- 1st phase – in time interval $(0, t_1)$ represents the initial pressure rise, which is influenced by the charge arrangement and the igniting source used (detonator). The pressure course in this phase is influenced by the consecutive ignition of the charge burning surface, however it proceeds the short part of the phase duration only. The pressure course in this phase is much more influenced by quick temperature increase of combustion products and air mixture in the closed vessel free volume.

- 2nd phase – in time interval (t_1, t_2) is the main phase of the black powder charge burning and the most part of charge burns off during it.
- 3rd phase – in interval (t_2, t_3) represents the remaining part of the charge burning out. It can be influenced by consequent burning surface rise at the 1st phase as well as by substantial unevenness of geometric dimensions and shapes of individual grains. This phase has the secondary meaning from black powder charge burning point of view.

3. Process of Acquired Data Evaluation

One of possible methods of the burning law determination is the test of given propellant burning in ballistic bomb. The same method can be used in case of black powder. The real record of measured pressure course in time $p = p(t)$ is obtained through the experiment (see Fig. 2). The 1st phase of the charge burning can be prolonged due to slower flame expansion on the all grains surface.

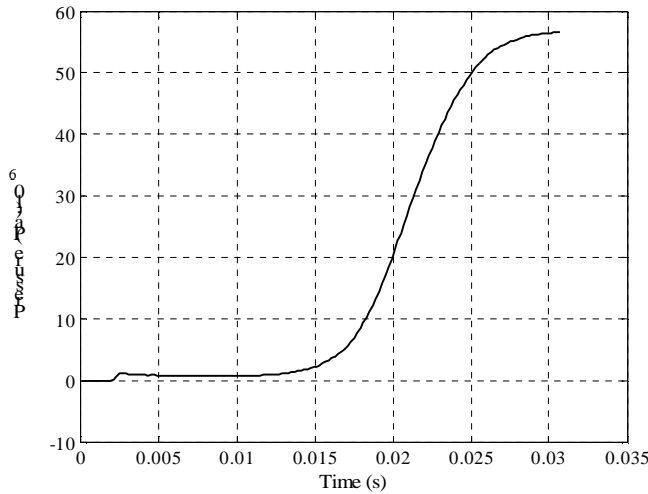


Fig 2 Measured pressure course of black powder charge burning in closed vessel.

The important value for burning law determination is relative burned mass y which can be expressed by relation [3]

$$y = \frac{m_{pb}}{m_p}, \quad (1)$$

where m_{pb} is burned mass of propellant (black powder) charge in time interval $(0 \div t)$ and m_p is total propellant charge mass. The relative burned mass y takes the values in interval $(0 \div 1)$ only.

The dependence of pressure on relative burned mass is given by the equation [3]:

$$p = \frac{m_p c(r_p T_{bp}) y}{V_{F0} - a m_p y - (1-y) \frac{m_p}{r_p}}, \quad (2)$$

where V_{F0} is initial free volume of the used ballistic bomb, $(r_p T_{bp})$ is specific heat energy of propellant charge, r_p is propellant density, a is propellant co-volume and c is heat losses coefficient.

The eq. (2) pays under condition that the source of heat energy needed for the black powder charge initiation does not create the pressure rise or the value of this pressure is negligible to pressure p_1 . The eq. (2) can be converged

$$p = \frac{y}{K_1 - K_2 y}, \quad (3)$$

where substitutions K_1 and K_2 are

$$K_1 = \frac{1}{c(r_p T_{bp})} \left(\frac{V_{F0}}{m_p} - \frac{1}{r_p} \right), \quad K_2 = \frac{1}{c(r_p T_{bp})} \left(a - \frac{1}{r_p} \right)$$

When differencing eq. (3) we get:

$$\frac{d p}{d y} = \frac{K_1}{(K_1 - K_2 y)^2}. \quad (4)$$

The value of heat losses coefficient c can be calculated from equation (3) by following manner. When putting $y = 1.0$ for time $t = t_3$ (at the end of black powder charge burning) and $c = 1.0$ (the heat losses do not affect the process) into eq. (2), we obtain the theoretical value of maximum pressure

$$(p_{p \max})_t = \frac{m_p (r_p T_{bp})}{V_{F0} - \frac{m_p}{r_p}}. \quad (5)$$

In fact, we evaluate the real maximum pressure $p_{p \max}$ from experiment. The value of heat losses coefficient is determined by comparison of real maximum pressure value and the theoretical one:

$$c = \frac{p_{p \max}}{(p_{p \max})_t} = \frac{p_{p \max}}{(r_p T_{bp})} \left(\frac{V_{F0}}{m_p} - \frac{1}{r_p} \right). \quad (6)$$

It is further obvious from the relative burned mass definition that

$$d m_{pb} = m_p d y. \quad (7)$$

The charge burned mass differential can also be expressed using the instantaneous mass emission \dot{m}_{ep} of gaseous combustion products from black powder charge burning surface

$$d m_{pb} = \dot{m}_{ep} dt = S_p u_p r_p dt. \quad (8)$$

When using the exponential form of black powder burning law:

$$u_p = u_0 p^a, \quad (9)$$

then from eqs. (7) and (8) we have

$$m_p d y = S_p u_p r_p dt,$$

where from

$$\frac{dy}{dt} = \frac{S_p u_p r_p}{m_p} = \frac{S_p u_p}{V_p}. \quad (10)$$

V_{p0} is initial black powder charge volume

$$V_{p0} = \frac{m_p}{r_p}. \quad (11)$$

Using the eq. (10) the derivative of pressure to relative burned mass is

$$\frac{dp}{dy} = \frac{dp}{dt} \frac{dt}{dy} = \frac{V_{p0}}{S_p u_p} \frac{dp}{dt}. \quad (12)$$

Substituting the eq. (3) and converting we obtain equation for experimental course of burning surface of black powder charge:

$$S_p = \frac{V_{p0}}{K_1 u_p} (K_1 - K_2 y)^2 \frac{dp}{dt}, \quad (13)$$

which is valid for time interval $t \in (t_1 \div t_3)$. However, the results of such calculation approach are not sufficiently precise. The better way is using of chosen geometric shape characteristics for the instantaneous burning surface calculation. The instantaneous volume of black powder charge in case of chosen sphere shape of black powder grain is:

$$V_p = \frac{4}{3} p (e_{0p} - e)^3. \quad (14)$$

It can be also expressed as function of relative burned mass, as follows

$$V_p = \frac{m_p (1-y)}{r_p} = V_{p0} (1-y). \quad (15)$$

The instantaneous burning surface is

$$S_p = 4p (e_{0p} - e)^2. \quad (16)$$

If we multiply eq. (16) by (14) and simultaneously divide by (15), the burning surface is

$$S_p = 3V_{p0} \frac{(1-y)}{e_{0p} - e}. \quad (17)$$

The similar relationship can be found also for other possible geometric shapes of the black powder grain.

4. Experimental Black Powder Burning Law

The experimental data of the black powder testing in closed vessel were obtained from Research Institute of Industrial Chemistry Pardubice – Semtín. Pressure courses were recorded with time difference $\Delta t = 0.0002$ s. The free volume of used closed vessel was $V_{p0} = 5.5 \times 10^{-6}$ m³. The testing black powder charge mass was $m_p = 1.1 \times 10^{-3}$ g. The type of black powder was T1-2. Its previously obtained burning law is introduced in [1] in form:

$$u = 2.33317 \times 10^{-5} p^{0.48285} . \quad (18)$$

For the burning rate determination we need to calculate the value of relative burned mass for each pressure value corresponding to the time from interval $(t_1 \div t_3)$ using equation that we get by conversion of eq. (3):

$$y_i = \frac{p_i K_1}{1 + p_i K_2} \quad (19)$$

The relation between the relative burned mass y and the burned web thickness e can be found from eq. (10) when we substitute the burning rate from difference equation as follows:

$$u_p = \frac{\Delta e}{\Delta t} . \quad (20)$$

The change of web thickness is as follows:

$$\Delta e = V_{p0} \frac{\Delta y}{S_p} . \quad (21)$$

The instantaneous burning surface of black powder charge is calculated from eq. (17). The value of the instantaneous burning rate at this time step is then determined from eq. (20) for time difference Δt . Results of solution are presented in Fig 3. The curve vibration at the end of burning rate course is caused by above introduced simplified determination of burning surface (all grains have the same shapes) which does not correspond to real burning surface mainly at this phase of black powder charge burning.

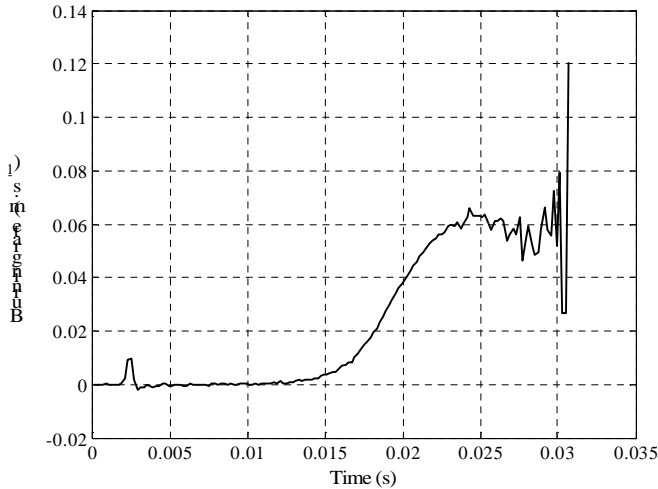


Fig. 3 Evaluated black powder burning rate course

The real course of burning rate is valid only in time interval for 2nd phase, i.e. (t_1, t_2) (see Fig. 1). Therefore we estimate the time t_1, t_2 from the graph of burning rate vs. time and the data corresponding to this interval we use for the evaluation of spare function of experimental burning law. The parameters of the burning law are then

evaluated from these data by the help of linear regression using the least squares method. The result of computing is the burning law of given type of black powder in form

$$u = 4.2881 \times 10^{-8} p^{0.81253} .$$

The correlation coefficient of the regression carried out is 0.99452. Fig. 4 presents comparison of the burning rate vs. real pressure course, the burning rate as the spare function course and previous form of burning law spare function.

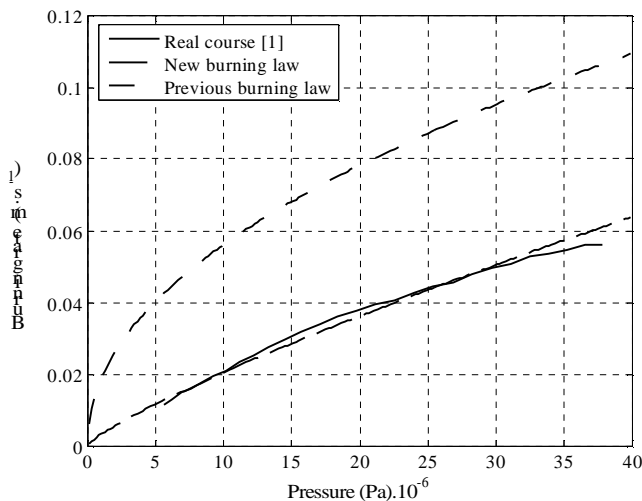


Fig. 4 Dependence of burning rate on pressure

5. Conclusion

The improved process of the black powder burning law determination is described in this paper with the use of the acquired data from the tests of black powder burning in closed vessel (ballistic bomb). The carefully acquired data sets obtained by means of the measurement facility of high quality and the modern software used for evaluation of these data sets enable more precise determination of experimental relationships and parameters which are necessary for improvement of internal ballistics solutions accuracy. The obtained black powder burning law is further used in solutions of solid propellant rocket motor igniters or cartridge charge igniters of barrel weapons.

References

- [1] LUDVÍK, F. Zákon hoření černého prachu pro zažehovače raketových motorů na tuhou pohonnou hmotu. [Burning Law of Black Powder for Igniters of Solid Propellant Rocket Motors]. *Journal of Military Academy in Brno, series B*, 1977, No. 2. p. 41-54.
- [2] LUDVÍK, F. Vliv velikosti zrn zážehové složky na charakteristiky zažehovače. [Effect of Ignition Composition Grains Magnitudes on Igniter Characteristics]. In *Journal of Military Academy in Brno, series B*, 1987, No. 1, p. 51-63.

- [3] KONEČNÝ, P., LUDVÍK, F., KUTTELWASCHER, V., ŠIMÁČEK, M. Výzkum dějů v raketovém motoru na tuhou pohonnou hmotu. [Research of Actions in Solid Propellant Rocket Motor]. [Studie projektu specifického výzkumu katedry raketové techniky]. Brno : University of Defence, 2005. p. 34.

Acknowledgement

The work presented in this paper has been supported by the Ministry of Defence of the Czech Republic (research project No. MO0FVT0000404).