Design of ballistic chamber for certification tests of crushers

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Abstract. This paper presents a design process of ballistic chamber for certification tests of crushers, including all design’s steps from conceptual design to shooting tests. This issue has been raised, because so far, all certification tests were carried out only by shooting tests, which was associated with high costs and large amount of effort. Therefore design of ballistic chamber for certification tests of crushers was aimed at reducing costs, including the reduction of the amount of necessary equipment. Design process of ballistic chamber for certification tests of crushers consists of a few steps, which were thoroughly described in the article. In the first step basic parameters of the ballistic chamber was calculated and in the second step, based on obtained results, 100 mm BS-3 barrel gun was adapted to carrying certification tests of crushers. In the third step the charge was fired in the ballistic chamber and the pressure graph was obtained. Next the pressure graphs from the ballistic chamber have been compared to analogous pressure graphs from the 100 mm BS-3 barrel gun (in which certification tests of crushers were usually carried out). Comparison has shown that the ballistic chamber can be used for certification tests of crushers and also for the ballistic tests of charges in the dynamic conditions, as in real shooting process.

1. Introduction
This paper presents a design process of ballistic chamber for certification tests of crushers. This issue has been raised, because so far, all certification tests were carried out only by shooting tests, which was associated with high costs and large amount of effort. Therefore design of ballistic chamber for certification tests of crushers was aimed at reducing costs, including the reduction of the amount of necessary equipment.

2. Design of ballistic chamber
Due to the fact that the certification tests of crushers were carried out by shooting from 100 mm BS-3 cannon the ballistic chamber was designed in order to simulate a real cannon shot. Mechanical construction and ballistic parameters were selected according to the real conditions occurring the shooting tests.

2.1. Mechanical model
The base part of ballistic chamber is a modernized cartridge chamber from 100 mm BS-3 cannon, presented in the figure 1.
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The barrel (e) has been cut to the length 846 mm. Its cylindrical part with the transition cone has been turned on the diameter 104 mm. The muzzle has been block by the metal plug (h), connected with the use of shrinkage method with the barrel. The steel nozzle (i) has been screwed in the metal plug. The nozzle has short cones: convergent and divergent and elongated cylindrical part, what should provide the nozzle much longer life. Barrel from the back, is bolted by the breechblock (b). All parts are placed in 100 mm BS-3 cannon base (a). For opening the breechblock and initiating a shot the original breechblock’s mechanisms have been used. Propellant charge (c) has been placed in modernized metal case (f) cut to the length of 500 mm and covered by the cellulosic cap (g). In the bottom of the metal case have been made an eccentric hole for the piezoelectric pressure sensor (l) and the channel for cable exit. Installing the piezoelectric pressure sensor on the bottom of metal case is very troublesome, but it was necessary to put it in the same place as tested crushers (k). To keep the 19 crushers (with 7 cm³ volume each) in the bottom of the metal case special container (j) and montage disc (m) have been designed. The design of the container provides the access of propellant gases to all crusher’s surfaces and prevents crushers from moving inside the ballistic

Figure 1. Mechanical model of ballistic chamber for certification tests of crushers: (a) 100 mm BS-3 cannon base, (b) breechblock, (c) propellant charge, (d) perforated metal tube, (e) barrel, (f) modernized metal case, (g) cellulosic cap, (h) metal plug, (i) steel nozzle, (j) crusher’s container, (k) crushers, (l) piezoelectric pressure sensor, (m) mounting disc, (n) igniter.
chamber. Propellant charge is initiated by the black powder placed in perforated metal tube (d), installed in the container and set over the igniter (n).

2.2. Calculations of the chamber with propellant gases flow through the nozzle

The main issue is to calculate the critical diameter of the nozzle and propellant charge parameters in order to achieve propellant gases pressure as close to real cannon shot as possible. During the solving the main problem of internal ballistics for ballistic chamber with propellant gases flow through the nozzle the following assumptions were made:

1. Propellant combustion process in accordance with the geometric law of combustion.
2. The propellant burning rate is proportional to the propellant gas pressure.
3. Propellant burns at average propellant gas pressure.
4. Throwing out of unburned propellant grains through the nozzle was ignored.
5. The ignition of propellant charge is instantaneous and simultaneous in the whole volume of propellant charge.
6. The value $K = c_p/c_v$ has been taken as the average and constant for the entire combustion process.

Combustion process of propellant charge in ballistic chamber with nozzle can be divided in two periods. First one from the moment of ignition to the total propellant charge burn with maximum value of propellant gases pressure $p_m$over time $t_m$. Second one from the time $t_m$ to the moment of total propellant gases flow out. The function $p(t)$ of propellant gases in ballistic chamber with nozzle was calculated based on the dependences [1]:

\begin{align*}
\text{for the first period} & \quad p_1 e^{t/\tau} & (1) \\
\text{for the second period} & \quad p = p_m/(1 + \beta t)^{2k/k-1} & (2) \\
\tau = W_\alpha \cdot J_k/f \cdot \omega \cdot (1 - \eta_k) & (3) \\
W_\alpha = W_0 - \alpha \cdot \omega + a/2 & (4) \\
J_k = e_1/u_1; & (5) \\
Y_k = \int G_{sek} \cdot dt & (6) \\
G_{sek} = A \cdot S_m \cdot p & (7) \\
K = c_p/c_v & (8)
\end{align*}

ignition pressure $p_1 = 5$ MPa

$\beta$ - propellant force

$\omega$ - propellant weight

$p$ - propellant gas pressure

$S_m$ - cross-sectional surface of nozzle

$A$ - gas outflow coefficient

$\alpha$ - covolumen

$k$ – adiabatic exponent

$\eta_k$ – projectile position in the moment of total propellant charge burned coefficient

$W_0$ – chamber volume

$\beta$ – Drozdow’s loading parameter

$e_1$ - half thickness of combustible layer

$u_1$ - burning speed

Calculations were carried out for three types of propellant charges (based on NC 7/7 nitrocellulose 7 – channel propellant, NC 9/7 nitrocellulose 7 – channel propellant and NC 12/7 nitrocellulose 7 – channel propellant), three loading densities, and for three critical diameters of nozzle. The results are presented in the figures 1 – 3 in the subsection 2.3.2.
2.3. Analysis of the calculations results in relation to real shot parameters

In order to analyze the calculations results in relation to real shot shooting tests from 100 mm BS-3 cannon have been carried. Five 100 mm OF-412 rounds with inert projectiles and with propellant charge containing 5,485 kg NDT-3 18/1 nitroglycerin 1–channel propellant were fired. During each shot the pressure of the propellant gases and time to reach maximum pressure were measured. For measuring pressure of the propellant gases piezoelectric pressure sensor and 7 cm³ volume crushers were used in the same time.

2.3.1. Shooting tests results were presented below and in the figure 2.

1. Max. pressure of propellant gases measured by piezoelectric sensor \( p_{ms} = (295 \div 320) \, MPa \)
2. Max. pressure of propellant gases measured by crushers \( p_{ms} = (284.7 \div 287.1) \, MPa \)
3. Time to reach max. pressure of propellant gases \( t_m = (5.6 \div 5.8) \, s^{-3} \)

![Figure 2. Example graph of propellant gases pressure over time from shooting tests from 100 mm BS-3 cannon using 100 mm OF-412 inert rounds.](image)

2.3.2 Calculations results were presented in the figure 3. The average measured time of reaching maximum propellant gases pressure \( t_m \) during the shooting tests from 100 mm BS-3 cannon was marked on the graphs.
Figure 3. Calculations results for NC 7/7, NC 9/7 and NC 12/7 propellants.
2.3.3 Conclusions from the analysis of the calculations results and shooting tests results were formed:

1. Increase of propellant gases pressure over time in ballistic chamber, was too high for NC 7/7 propellant and too low for NC 12/7 propellant in comparison with increase of propellant gases pressure for the other propellants.
2. Propellant gases outflow was too slow for critical diameter of nozzle $d_c = 25\, mm$ (slightly sloping part of graph).
3. Time of reaching maximum propellant gases pressure $t_m$, for NC 9/7 propellant and critical diameter of nozzle $d_c = 30\, mm$, was the most similar to average measured time of reaching maximum propellant gases pressure during the shooting tests.

2.4. Comparative shooting tests

Based on the conclusions of analysis NC 9/7 propellant and nozzle with critical diameter $d_c = 30\, mm$ were selected for shooting tests to compare calculations results with measured parameters from the experiment and also to compare the results from shooting tests in ballistic chamber with the results from cannon shots. During each shot the pressure of the propellant gases and time to reach maximum pressure were measured. For measuring pressure of the propellant gases piezoelectric pressure sensor and 7 $cm^3$ volume crushers were used in the same time. Obtained results were presented in the table 1 and figure 4.

Table 1. Shooting tests results for NC 9/7 propellant and nozzle with critical diameter $d_c = 30\, mm$.

| Shot No. | $\omega$ (kg) | Maximum pressure CRUSHER (MPa) | Maximum pressure PIEZOELECTRIC SENSOR (MPa) | $t_m$ (ms) |
|----------|---------------|--------------------------------|---------------------------------------------|------------|
| 1        | 3.20          | 348.0                          | 310                                         | 6.5        |
| 2        | 3.30          | 364.4                          | 370                                         | 5.5        |
| 3        | 3.40          | 381.8                          | 345                                         | 5.5        |
| 4        | 3.45          | 380.3                          | 360                                         | 5.5        |
| 5        | 3.48          | 387.9                          | 370                                         | 5.5        |
| 6        | 3.50          | 386.3                          | 420                                         | 5.5        |
| 7        | 3.50          | 393.9                          | 410                                         | 5.5        |
Figure 4. Example graphs of propellant gases pressure over time for NC 9/7 propellant and nozzle with critical diameter $d_c = 30 \text{ mm}$.
2.4.1 *Analysis of the comparative shooting tests results* allows to state that:

1. The shape of propellant gases pressure graph obtained in the calculations process only slightly differs from the shape of graph obtained during the shooting test. Also the similarity between the shape of propellant gases pressure graph obtained in the shooting tests from the ballistic chamber and from the 100 mm BS-3 cannon is good enough.

2. The rising part of the propellant gases pressure graph obtained during the shooting test is jagged probably because the ignition system is inappropriate for propellant charge used during the test.

3. Time to reach maximum propellant gases pressure is almost the same for the results of calculations, shooting test from ballistic chamber and shooting tests from 100 mm BS-3 cannon.

4. Maximum propellant gases pressure measured, using the piezoelectric sensor, during the shooting tests from the ballistic chamber is much higher than the pressure measured using the piezoelectric sensor during the shooting tests from 100 mm BS-3 cannon and contains in the range of 310 – 410 MPa, depending on propellant weight. This range is satisfying, because the working pressure for crushers is 400 MPa.

3. **Nozzle’s erosion process**

Due to the fact that the ballistic chamber nozzle is to be used regularly for certification tests of crushers, it was necessary to examine the nozzle erosion process and its influence on the ballistic parameters.

2.5. *Shooting tests of nozzle’s erosion*

Shooting tests were carried out using two nozzles, made of 35HGS steel, with critical diameters $d_{c1} = 29.9 \text{ mm}$ and $d_{c2} = 34.9 \text{ mm}$. During each shot maximum pressure of the propellant gases and critical diameter of nozzles were measured. For measuring pressure of the propellant gases 7 cm$^3$ volume crushers were used. Obtained results were presented in the tables 2 - 3 and the dependence of the diameter increase over the number the shots were presented in the figures 5 – 6.

| Shot No. | $\omega$ (kg) | Maximum pressure CRUSHER (MPa) | Critical diameter (mm) | $\Delta d_c$ (mm) |
|----------|---------------|--------------------------------|-----------------------|------------------|
| 1        | 3.00          | 347.8                          | 30.4                  | 0.5              |
| 2        | 3.20          | 378.8                          | 30.9                  | 1.0              |
| 3        | 3.30          | 398.8                          | 31.4                  | 1.5              |
| 4        | 3.20          | 392.7                          | 31.9                  | 2.0              |
| 5        | 3.25          | 389.2                          | 32.4                  | 2.5              |
| 6        | 3.30          | 393.1                          | 32.9                  | 3.0              |
| 7        | 3.35          | 393.1                          | 33.4                  | 3.5              |
| 8        | 3.40          | 401.8                          | 33.9                  | 4.0              |

Table 2. Shooting tests results for nozzle with critical diameter $d_{c1} = 29.9 \text{ mm}$. 

NOZZLE WITH CRITICAL DIAMETER $d_{c1} = 29.9 \text{ mm}$
Figure 5. Changes in the critical diameter of the nozzle $d_{c1}$ in dependence of the number of shots.

Figure 6. Changes in the critical diameter of the nozzle $d_{c2}$ in dependence of the number of shots.
2.6. Analysis of the nozzle’s erosion shooting tests results

1. The shooting tests show that nozzle’s erosion is regular. Based on obtained graphs, presented in the figure 4 and figure 5, it can be stated that the erosion is linear, and with lower initial critical diameter the erosion process is more intensive.

2. Influence of increasing the critical diameter on maximum propellant gases pressure is relatively small. Keeping the value of maximum propellant gases pressure, in ballistic chamber, on a constant level is possible by increasing the weight of propellant charge.

3. Designed nozzle service life is about 20 shots, which allows to carry two certification tests of crushers using one nozzle.

4. Conclusions

1. Exchangeability nozzles with critical diameter $d_c = 30 \text{ mm}$ provide the proper propellant gases efficiency per second during the shot, using the propellant charge based on NC 9/7 nitrocellulose 7 – channel propellant.

2. Shape of propellant gases pressure graphs obtained during the shooting tests from ballistic chamber and 100 mm BS-3 cannon are similar and the measured time to reach maximum propellant gases pressure is almost the same for ballistic chamber and 100 mm BS-3 cannon.

3. Using propellant charges based on 3.5 kg NC 9/7 nitrocellulose 7 – channel propellant and nozzle with critical diameter $d_c = 30 \text{ mm}$ provide the proper crusher’s working pressure.

4. Designed ballistic chamber with nozzle may be used for certification tests of crushers and also for ballistic tests of propellants and different type of charges in the conditions of dynamic rise and fall of propellant gases pressure as in real shot.

5. References

[1] Sieriebiakow M 1955 Interior ballistics MON Warsaw