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Compacted Modified Propellant Blocks as Traveling Charge in the Hybrid Shot Scheme

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Abstract: The burning of compacted modified propellant charges applied as a traveling charge in the hybrid shot scheme was studied. The block charges were manufactured by pressing fine propellant grains coated by a thin film of polyvinyl butyral. A stick from several pressed pellets was insulated over its lateral surface by a thin layer of silicon paste, glued to the back of the projectile and inserted into the barrel of the 23-mm smooth-bore laboratory gun. The loose-packed accelerator charge was placed in the breech. Combustion was initiated by an igniter plug placed between the traveling and breech charges. A set of piezo-quartz gauges placed in the breech and along the barrel, as well as a frame-target device were used for recording characteristics of the firings. It is shown that blocks of this type, applied as the traveling charge, provide a stable burning process resulting in high ballistic performance. The block traveling charge preserves its integrity in the course of its motion along the barrel, and burning envelopes its total mass when pressure in the breach passes the maximum value. The descending portion of the pressure diagram demonstrates appreciable transformation, with convex or secondary hump sections. The shape of spatial pressure profiles behind the moving projectile is also transformed, and the pressure at the projectile butt end may be higher than the pressure in the breech. Compared to the conventional charges at the same maximum pressures the muzzle velocity increment attains 340 $m\,s^{-1}$ (or 23%) for a light 35-g projectile and 200 $m\,s^{-1}$ (or 19%) for a heavy 104-g projectile.

Keywords: Traveling charge · Convective burning · Propellant blocks · Muzzle velocity increment

1 Introduction

The concept of traveling charge aims to increase the muzzle velocity and consists of the following. The propellant charge is (partially or totally) attached to the projectile and burns up in the course of its joint movement together with the projectile along the barrel. Although the mass of the projectile increases due to adding the traveling charge mass, and hence, the initial acceleration of the projectile calls responsible for higher energy, it is more than compensated by several positive factors: reactive thrust, reduced velocity of the gas being entrained after the projectile, and enhanced pressure at the projectile rear end. Theoretical considerations [1–3] predict with confidence the positive effect, emphasizing that the high increment of the muzzle velocity can be expected for the high-velocity projection systems with the ratio of the charge mass to the projectile mass to be high, and when the difference of pressures in the breech and at the projectile reaches high values.

Investigations on the traveling charge were conducted several years ago. One of the first studies was conducted by the German scientist Langweiler [4], who worked at the WASAG, Reinsdorf, Westphalia, in 1939–1943. After the end of the Second World War, documents with the results of these studies went, together with the captured archives, to the USA and were recognized as a basis for the extensive research during 1950–1989. The detailed description of these works and the list of publications can be found elsewhere [5]. However, investigations on these fields have apparently been stopped, firstly, for the lack of the positive experimental confirmations of the traveling-charge effect, as well as due to an explosion accident, which happened when a fast-burning propellant was tested to get the very high combustion rates recognized as necessary for the traveling charge application. Nevertheless, these studies were of value and contain extensive scientific matter.

Various ways to fabricate the traveling charges have been tested, including bundles of propellant sticks or multi-perforated tubes; compacted assembly of thin propellant plates of different configuration sometimes with additional orifices; porous pressed charges fabricated from double-base propellant balls or fibers, or from a mixture of

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ammonium perchlorate and double-base fine-grained propellants, or from porous nitrocellulose; and cast blocks of fast-burning propellants, mainly, of boron-hydride-based composite propellants.

The hybrid scheme with the charge divided into the accelerator, a charge placed in the breech, and the traveling charge, which fitted to the projectile, was studied. The projectile is, typically, a cylindrical metal body with sealing rings. The back end of the projectile is either flat or has a cavity, in which the head of the traveling charge was tightly inserted. The lateral side of the block traveling charge, which was outside the projectile, was coated with a layer of insulating material (typically, nitrocellulose). In order to vary the ignition delay of the block traveling charge, its open end was covered with a pellet of a slow-burning propellant.

The most stable data were obtained with the traveling charge fabricated from the bundle of multi-perforated propellant tubes attached to the projectile. The pressure diagram recorded in the breech has a secondary hump on the descending section, related to the traveling charge burning. The muzzle velocity increment in comparison to the classical charge in the 20-mm smooth-bore gun was up to 8% which seems insufficient. The reason was recognized as the low burning rate and researchers switched over to the fast-burning compositions. However, the combustion of the porous block charges typically generated strong pressure oscillations, and the reproducibility of ballistic performance was rather poor. Because of the instability of burning and small increment of the muzzle velocity these investigations were terminated. One can suppose that the source of failure lies in the lack of knowledge of the behavior and properties of convective burning in charges with a low gas-permeable porosity.

A significant part of investigations were carried out on monolithic blocks of fast-burning composite propellants (VHBR propellants or formulations) fabricated from boron hydride, oxidizer, and binder. Ballistic investigations were conducted in the 40-mm smoothbore laboratory gun with a breech, which had the same diameter as the barrel. Besides, the extensive investigations into behavior and mechanism of burning for VHBR propellants were conducted. These firings were fulfilled in the closed bombs at pressures up to 200 MPa. The burning rate for various compositions was recorded in a range 1–500 $m\,s^{-1}$. At the high burning rates, strong pressure oscillations were observed. The ability of fast-burning propellants to produce significant jet force was experimentally demonstrated. For example, the stresses recorded at the base plate of a charge, which burnt with estimated rate of 300 $m\,s^{-1}$ were approximately two times higher than the gas pressure above the burning charge. The theoretical model of the fast burning of VHBR compositions was developed [6], based on assumptions that due to shear stresses generated in the charge during its burning, the rise of porosity takes place (a process named deconsolidation), with the subsequent developing of convective burning, increase in stresses and formation of a cloud of dispersed burning particles-conglomerates. The model qualitatively reproduces the burning stages and generation of the pressure oscillations observed in the closed bomb tests. Participation of porosity in the convective burning of VHBR compositions was demonstrated with use of the high-speed photography.

The muzzle velocity increment calculated with the theoretical model for the traveling charge from VHBR propellants equals up to 25%. However, experiments did not show anything similar. Finally, an accident taking place during the fabrication of the charge, which confirmed high explosive hazard of the studied propellants, together with the burning instability, strong pressure oscillations, and disappointment arising from lack of expected muzzle velocity increment led to the end of this research.

A recent publication on the traveling charge originally considered only theoretical aspects of the problem. However, in a following article [7], more information on experimental measurements in comparison to the classic charge is reported.

In Russian scientific literature, the traveling charge concept has been considered in a chapter of a book [1], which covers modern aspects of internal ballistics. Here are described the mathematical model, the investigation procedure, as well as results of parametric analysis of the hybrid shot scheme with the traveling block charge and some experiments conducted for verifying theoretical predictions. A comprehensive approach can be found in some conference reports [3,8–12]. The investigations cover some kinds of propellants tested for fabrication of the traveling charge.

The molded propellant material NTBS consists of a dispersed filling material (a fast-burning explosive of the benzotrifuroxane class), matrix (plasticized spherical nitrocellulose), and additives. The propellant has high energy; its technological porosity is of 2–3%. Burning of this propellant was studied in a closed bomb [8] and in a laboratory setup with streak-photo registration [10,11]. It was shown that the fast burning in a convective mode commences if pressure exceeds a threshold value P_c. Convective burning is connected with the gas permeability, which is formed in the compressed and deformed propellant body, though details of the mechanism are still unknown. The convective burning velocity changes in rather narrow range, typically 40–80 $m\,s^{-1}$, and weakly depends on pressure. It is shown, that the threshold pressure as well as convective burning velocity (to smaller degree) can be controlled by making changes of the propellant composition and the charge fabrication technique, in particular, by introducing an additive of fine-size aluminum powder [8]. Firings with the traveling charge fabricated from the NTBS propellant were conducted in a 23-mm laboratory gun and demonstrated stable burning and reproducibility of ballistic performance. The muzzle velocity increment in regard to the classic loose-packed charge (at the identical maximum pressure) exceeded 10%.

Interest in fast-burning propellants for application as the traveling charge was initiated by theoretical considerations, which predict that the traveling charge must burn at a rather high rate. Burning of the VHBR compositions is implemented in convective burning mode. The mechanism and behavior of this process are very complicated ones and poorly known in some aspects. However, there are high density block charges, in which convective burning propagates with stable velocities and is studied rather well. Those are the block charges of special kind fabricated by pressing from propellant grains coated over the outer surface by a thin polymer film. These charges named as compacted modified propellant charges (shortly, CMPC; in Russian their name is "high-density charges of convective burning") are well studied. There is extensive database on convective burning velocity depending on the grain size, charge density (porosity), the polymer film thickness, pressure, and burning conditions [13–16]. CMPC are tested in barrel systems as the breech charge. These firings have demonstrated stable and reproducible characteristics, which provide a marked increment of the muzzle velocity [15,17]. Examination of CMPC in the hybrid scheme with the traveling charge was evident. A preliminary study [11,12] has shown promising results. The objective of this paper is to describe these investigations in detail.

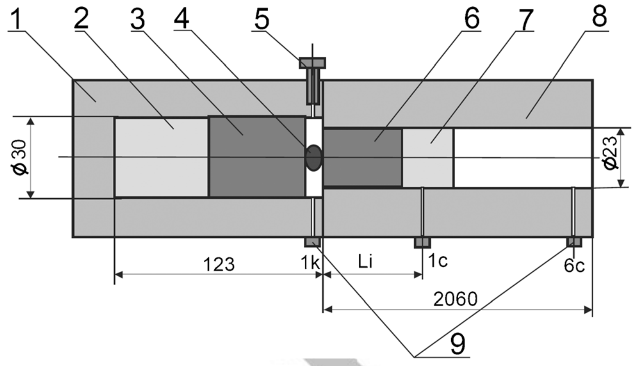

Figure 1. Schematic of charge configuration in 23-mm barrel setup: (1) breech, (2) insert to decrease the chamber volume, (3) booster located in the breech, (4) additional igniter, (5) igniter plug, (6) CMPC as traveling charge, (7) duralumin projectile, (8) barrel of 2.06 m long, (9) pressure gauges located from the barrel (*1k*) up to the muzzle (*6c*), and (*Li*) is the positions of the gauges along the barrel: 75 mm (*1c*), 220 mm (*2c*), 820 mm (*3c*), 1400 mm (*4c*), 1890 mm (*5c*), and 2050 mm (*6c*).

2 Conditions of Experiments

Firings with the traveling charge were filled in a 23-mm smoothbore laboratory gun with a barrel length of 2.06 m, which is instrumented by a set of piezo-quartz gauges of AVL type for recording pressure diagrams in the breech and in several points along the barrel, and by the frame-target device with a spacing of 1200 mm for recording the muzzle velocity. Schematic of the barrel setup is shown in Figure 1. The charge was composed of two parts. The part placed in the breech (the breech charge) was fabricated from grains of 7-perforated single-base propellant 4/7 and had loose-packed density. The traveling charge was composed from 1–3 pellets fabricated by pressing (up to porosity 10–20%) at preheating up to 60 °C from the propellant grains coated over their lateral surface with a thin film of polyvinyl butyral (PVB). The PVB film was put on the grain surface from 5-% alcoholic solution of PVB, which was sprayed over a grain layer permanently stirred. The treated grains were dried in an air stream, and then in a desiccator with temperature 60 °C up to the total removal of the alcohol. The PVB content was determined by weighing. The pellets were pressed under preset values of pressure, temperature, and persistence time. 1-perforated single-base grained propellants of types VTM and VU, as well as the ball propellant SFNC with porous grains of approx. 20% porosity were used. In order to evaluate the muzzle velocity increment attained due to the traveling charge, firings with classic loose-packed charge from the 7-perforated single-base propellant 4/7 were conducted. Table 1 shows the geometric properties of these propellant grains.

Before the firings in the gun, burning of the tested propellants in the unmodified state and in CMPC was studied with use of the standard closed bombs at pressures up to 200 MPa. In the unmodified state, a sample of the tested propellant of 8 g in mass was placed into a steel cup of 16 mm in internal diameter and 55 mm long. The block charges having also 8 g in mass were composed of sticks from a few pressed pellets of 12 mm in diameter. The side surface of the charge was insulated by a thin layer of epoxy adhesive. The finished charge was placed in the steel cup, the gap between cup wall and charge was filled

Table 1. Geometric sizes of the tested grain propellants [a].

Propellant	Grain diameter/ length [mm]	Perforation diameter [mm]	Specific outer/total surface area [cm^2 g^{-1}]	Hydraulic (effective) diameter, d0 [mm]	Web thickness [mm]
VU (single perf.)	0.51/1.31	0.1	61.7/71.7	0.61	0.21
VTM (single perf.)	0.89/1.5	0.16	37.1/42.8	1.0	0.37
Ball orous NC, SFNC	0.57/0.28	–	89	0.42	0.28
4/7 (seven perf.)	2.17/2.76	0.15	16.9/22.9	2.25	0.43

a) The specific area of the outer grain surface, A_s, was calculated from the mean geometric size listed in the table, short of the channel surface area. The effective grain diameter was calculated by formula $d_{ef} = 6/(\rho A_s)$, where ρ is the propellant TMD.

with glycerol. In a few firings, in order to determine the mean velocity of the burning wave propagation over the charge length, a 0.5-g mass of the fast-burning HE, benzotrifuroxane (BTF) was placed at the bottom of the cap under the charge tested. Fast burning of BTF generates a number of quickly damped pressure waves of 15–20 MPa in initial amplitude, which can be easily identified on the pressure diagram in the bomb. The burning process was initiated by igniter composed from 0.5 g of the black powder and 3 (or 5) g of pyroxylin cotton. Burning of the igniter produced in the bomb the pressure of 35–40 (or 60–65) MPa for the time interval of 1 ms.

3 Experimental Results

3.1 Firings in the Closed Bomb

Figure 2 shows the pressure diagrams recorded in firings with loose-packed charges composed of grains of VTM and SFNC propellants. Firings were conducted in bombs of different volume (85 cm^3 for VTM and 105 cm^3 for SFNC). The pressure diagram of the VTM propellant having the normal shape can be divided into a few sections: the initial piece of diagram with the pressure rise caused by the igniter burning, the following piece of a smooth rise related to the burning of the tested propellant up to the maximum point (at the time instant of ca. 4.2 ms), and the final pressure drop after finishing the propellant burning. In contrary, the pressure diagram of the SFNC propellant looks unusual: it begins with a series of the strong pressure peaks, which reflect circulation of the pressure waves in the bomb free space due to very fast burning of the tested propellant. Burning finishes by the time instant of 1 ms; and the amplitude of circulating waves decreases.

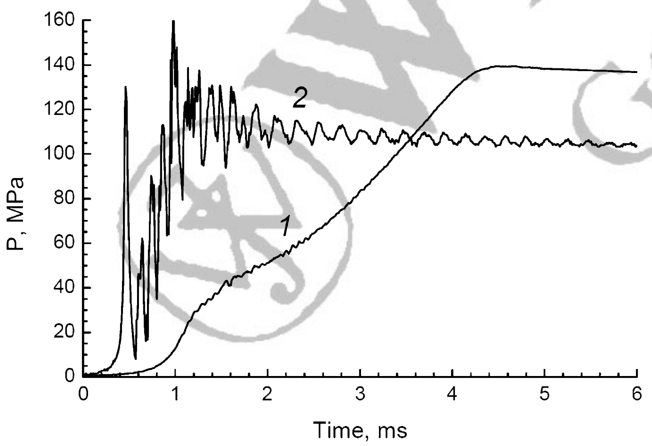

Figure 2. Pressure diagrams recorded in the closed bombs during combustion of 8-g samples of the loose-packed density composed from the VTM propellant (diagram 1, the bomb of 85 cm^3 in volume) and SFNC propellant (diagram 2, the bomb of 105 cm^3 in volume).

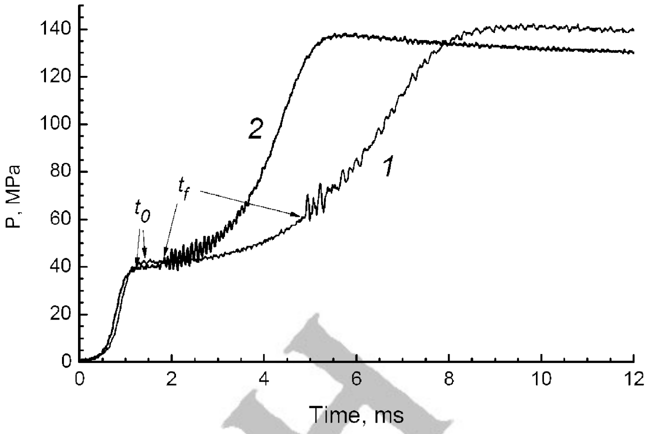

Figure 3. Pressure diagrams recorded in the closed bomb (85 cm^3 in volume) during combustion of CMPC fabricated from VTM + 1.4% PVB (1) and SFNC + 2.5% PVB (2). t_0 is the time instant when convective burning begins; t_f is the time instant when pressure oscillations induced by the very fast burning of a pinch of BTF placed at the charge bottom start.

Figure 3 shows the pressure diagrams recorded in firings with CMPC of 1.38 $g\,cm^{-3}$ in density, fabricated from the grains of the same VTM and SFNC propellants. Additionally, in order to determine the time instant when the flame front propagates over the total charge length, a 0.5-g pinch of BTF was put on the cup bottom. The pressure diagram recorded for the CMPC from the SFNC propellant has the normal shape in contrast to the same diagram for the loose-packed charge from unmodified grains due to coating with the thin PVB film, which is shown in Figure 2. The mean velocity of convective burning for the CMPC from the VTM grains equals 15 $m\,s^{-1}$ (in the pressure interval 40–55 MPa), and 80 $m\,s^{-1}$ for the CMPC from the SFNC grains (at the pressure 40 MPa).

3.2 Firings in the 23-mm Smoothbore Laboratory Gun

Figure 4 shows a photograph of the assembly composed of the traveling charge and projectile. The projectile was a simple cylinder from duralumin with no skirt or obturator. The traveling charge was composed from 2–3 pellets with a diameter of 22.9 mm glued one to another by a few spots of glue placed at their butt surface. The stick of pellets was glued to the projectile rear end, then its side surface was coated with the silicon paste, and the assembly inserted into the barrel so that the rear end of the traveling charge aligned with the barrel entrance. The silicon paste excess was carefully removed; then the breech with the breech charge was attached. The igniter (black powder 1 g + electric fuse) was placed in the gap between the breech and traveling charges.

Two series of firings were conducted with the light 35-g and heavy 104-g projectiles. The task of the first series was to increase the muzzle velocity closer to 2000 $m\,s^{-1}$, and the task of the second series was to verify the possibility of

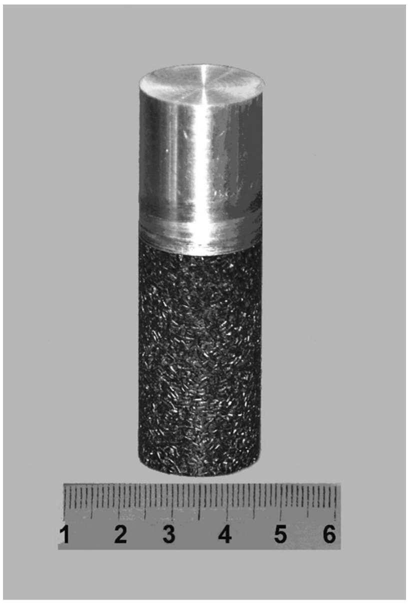

Figure 4. CMPC (below) glued to the projectile (above).

getting the muzzle velocity increment due to traveling charge at the significantly lower velocities. The mass of breech charge was kept constant, equal to 48.4 g in firings with the 35-g projectile and 41 g in firings with the 104-g projectile. The mass of traveling charge was varied from 40 up to 80 g in firings with the 35-g projectile and from 20 up to 50 g in firings with the 104-g projectile. Additionally varied were the PVB content, and porosity of CMPC. However, the best results were attained when the pellet adjacent to the projectile was fabricated from VU or SFNC propellants producing more intense burning.

Table 2 presents the conditions of firings and short results of measurements for a few typical firings. The columns devoted to the firing conditions comprise number of the firing, propellants used to fabricate the traveling charge, mass of the traveling charge with the masses of the separate CMPC pellets in brackets, densities of the CMPC pellets, length of the traveling charge, and total volume occupied with the charge. The columns devoted to the results comprise maximum pressure, integral of the pressure in the breech up to the instant when the projectile leaves the muzzle, and the muzzle velocity. Examples of the registrations for firings with the light 35-g projectile are shown in Figure 5, Figure 6, Figure 7, and Figure 8. One can notice that the pressure diagrams recorded in the breech differ significantly in their shape. So, in the firing T-41 (Figure 5) burning of the traveling charge manifests itself by the upwards convexity at a section of the descending pressure curve. Diagrams of such shape were observed in the firings with the traveling charge fabricated from propellant VTM or propellants VTM and VU. In the firing T-50 (Figure 6), half

Table 2. Conditions and summary results of firings conducted in the 23-mm laboratory barrel setup. Hybrid configuration with the top-ignited traveling charge and 4/7 accelerator [a].

Test No	Propellants used in the traveling charge ~~a)~~	Traveling charge mass (masses of CMPC pellets) [g]	TC length [mm]	Breech + traveling charge volume [cm^3]	Density of CMPC pellets [$g\,cm^{-3}$]	Pmax [MPa]	Ik [$MPa\,m\,s^{-1}$]	Vd [$m\,s^{-1}$]
35-g Projectile, accelerator from the propellant 4/7 of 48.4 g in mass								
T-41	VTM + 1.4% PVA/ VU + 2.2% PVA	55.1 (30/25)	96.5	97.8	1.40/1.35	355	445	1840
T-49	VTM + 1.4% PVB/ SFNC + 2.5% PVB	50.3 (25 + 10.3/15)	84.8	93	1.42 + 1.45/1.46	315	430	1813
T-50	VTM + 1.4% PVB/ SFNC + 2.5% PVB	49.8 (24.9/24.9)	84	92.7	1.42/1.46	336	458	1870
T-54	VTM + 2.8% PVB/ SFNC + 2.5% PVB	50.2 (25.1/25.1)	85.5	93.3	1.44/1.42	368	452	1780
T-58	VTM + 1.4% PVB	49.9 (25 + 24.9)	87	93.9	1.39/1.39	306	420	1722
T-64	VTM + 1.4% PVB/ SFNC + 2.5% PVB	70.1(30.1+25/15)	118.7	107.1	1.4 + 1.45/1.47	316	430	1905
104-g Projectile, accelerator from the propellant 4/7 of 41 g in mass								
Y-77	VTM2 + 2.6% PVB	44.6 (22 + 22.1)	72.8	81.2	1.49 + 1.45	289	517	1090
Y-85	VTM + 2.6% PVB/ VU + 1% PVB	54 (22 + 21.9/10.1)	88.4	87.5	1.49 + 1.50/1.44	296	548	1213
Y-87	VTM + 3.6% PVB/ VU + 1% PVB	59.9 (25 + 25/9.9)	98.3	91.6	1.49 + 1.49/1.46	312	564	1258
Y-88	VTM + 3.6% PVB/ VU + 1% PVB	65.8(30.4+25.4/10)	107.4	95.4	1.50 + 1.49/1.46	355	596	1283
Y-90	VTM + 3.6% PVB/ VU + 1% PVB	60.3 (28 + 25.9/6.0)	97.6	91.3	1.50 + 1.49/1.44	344	567	1241

a) In columns with masses and density, the sign "+" separates the values belonging to the different pellets fabricated from the same propellant, and the sign "/" separates the values belonging to the pellets fabricated from different propellants.

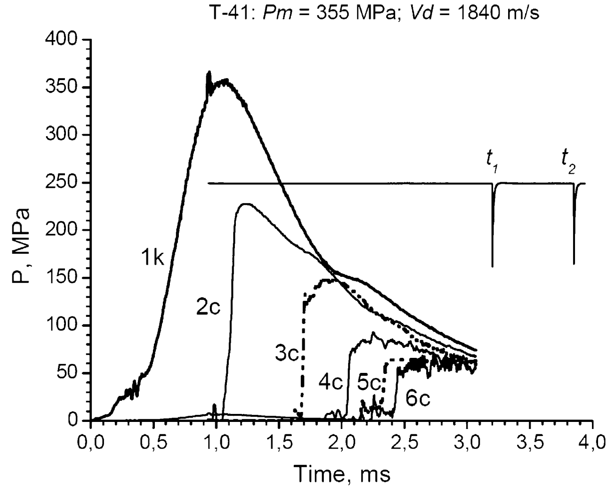

Figure 5. Pressure records at 6 points (*1k* in the breech and *2c–6c* along the barrel), and the signal of the frame-target device (with time instants t_1 and t_2 to determine the muzzle velocity) in the firing T-41 with the 35-g projectile.

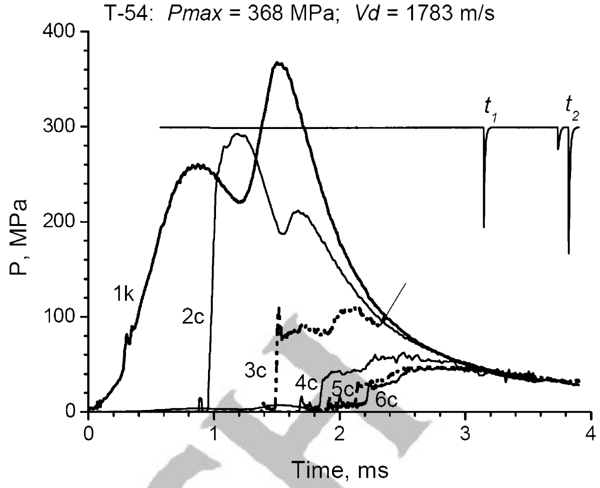

Figure 7. Pressure records at 6 points and the signal of the frame-target device in the shot T-54 with the 35-g projectile. Signs are the same as in Figure 5.

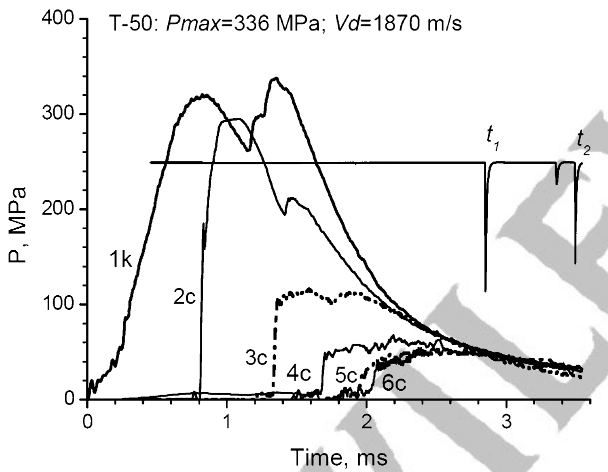

Figure 6. Pressure records at 6 points and the signal of the frame-target device in the shot T-50 with the 35-g projectile. Signs are the same as in Figure 5.

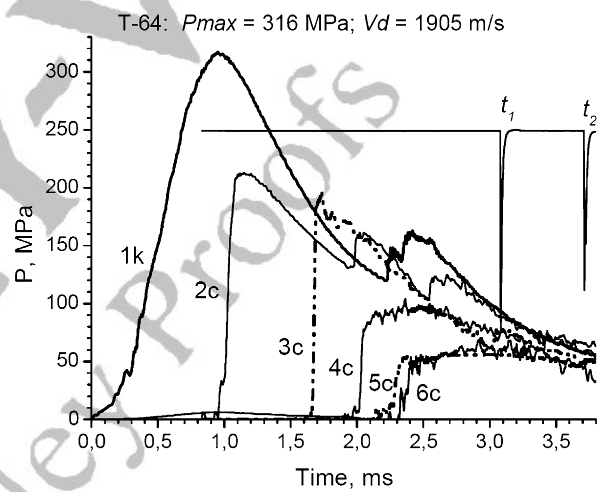

Figure 8. Pressure records at 6 points and the signal of the frame-target device in the shot T-64 with the 35-g projectile. Signs are the same as in Figure 5.

of the traveling charge was fabricated from propellant SFNC. Its burning resulted in the secondary pressure peak at the pressure diagram in the breech; the amplitude of this peak is approximately the same as the amplitude of the main pressure peak. In the firing T-54 (Figure 7) the pellet from the SFNC propellant had higher porosity than in the firing T-50. In this case, the amplitude of the secondary peak turned out to be markedly higher than the amplitude of the main peak connected with burning of the breech charge. Finally, in the firing T-64 (Figure 8) the secondary peak turned out to be shifted to the end section of the descending pressure curve. It is worth noting that this firing demonstrates the best ballistic performance.

The pressure diagrams of identical shape were also obtained in firings with the heavy 104-g projectile. An example of recordings presented in Figure 9 (firing Y-87) demonstrates the pressure diagram in the breech having two peaks of almost the same amplitude. The traveling charge for this firing was fabricated from propellant VTM and VU.

In total, there were 70 firings with the traveling charge conducted in attempts to get the highest muzzle velocity by varying the charge properties. The summarized results of these attempts are presented in Figure 10 in a plot of the muzzle velocity against the maximum pressure. In order to evaluate the muzzle velocity increment provided by the traveling charge, control sets of firings were conducted with the conventional charge (without traveling

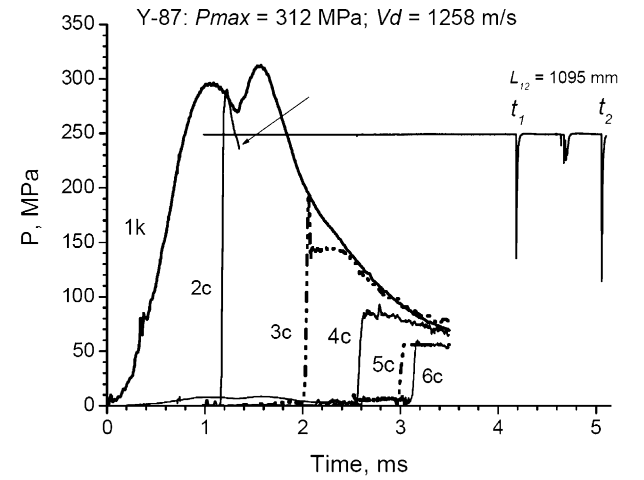

Figure 9. Pressure records at 6 points and the signal of the frame-target device in the shot Y-87 with the 104-g projectile. Signs are the same as in Figure 5. Distance between frames was reduced in this firing up to 1095 mm; arrow indicates time instant when the signal of the gauge 2c was terminated due to a technical reason.

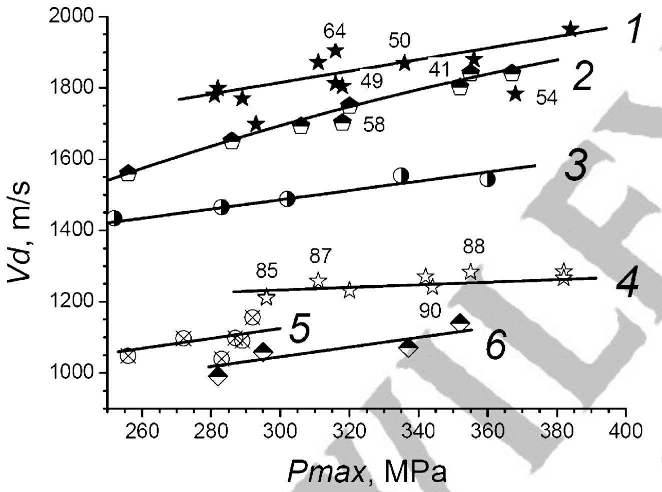

Figure 10. Summary data on dependence of the muzzle velocity on maximum pressure in the breech. Series of firings with the 35-g projectile: (1) traveling charge fabricated from propellants VTM + SFNC, (2) traveling charge fabricated from propellants VTM or VTM + VU, (3) conventional charge; Series of firings with the 104-g projectile: (4) traveling charge fabricated from propellants VTM + VU, (5) traveling charge fabricated from propellant VTM, (6) conventional charge. Numerals indicate numbers of firings from Table 2.

charge) composed from propellant 4/7. In these sets of firings the projectile had a raised band of 23.2 mm in diameter for sealing the breech. In order to cover the maximum pressure interval, which was realized in firings with traveling charge, the control firings were conducted varying the charge mass in the range of 56–80 g in series with the 35-g projectile, and of 48–62 g in series with the 104-g projectile. In order to keep the loading density constant (0.81–0.83 g cm^{-3}), the breech volume was varied simultaneously. The results of these sets of firings are also presented in Figure 10.

Analysis of these data shows that firings with the traveling charge and light projectile can be divided into two groups which are localized near the corresponding mean lines. The first group (line 2) is composed of the firings with the traveling charge fabricated from either VTM propellant or propellants VTM and VU. The muzzle velocity increment attained in this group, in comparison to the control firings, is 250 m s^{-1} at the identical maximum pressure. The second group is composed of the firings in which the porous propellant SFNC substituted for a part of the traveling charge from 15 up to 25 g in mass. In these firings the muzzle velocity came near 2000 m s^{-1}, and the increment exceeded 350 m s^{-1}, which is ca. 23 % of the muzzle velocity in control firings with the conventional charge. Concerning the other varied factors, their effect turned out to be insignificant.

The data obtained for the heavy projectile can be also divided into two groups. The first group (line 5) comprises firings with the traveling charge fabricated from the propellant VTM. The second group (line 4) comprises firings, in which a part of the traveling charge (from 5 to 10 g in mass) adjoining the projectile was fabricated from the propellant VU. Pressure diagrams recorded in these firings demonstrate the secondary peak. Reducing the VU pellet mass up to 5–6 g, the amplitude of the secondary peak was less than the main one. The muzzle velocity increment has reached 200 m s^{-1} or ca. 19 % of the muzzle velocity in control firings with the conventional charge.

Signals of pressure gauges placed along the barrel can be used to plot the projectile trajectory. Abrupt deflection of the gauge signal enables one to determine exactly the time instant when the projectile passes the point where this gauge is located. Figure 11 presents an example of the projectile trajectory plotted for the firing Y-87. The muzzle velocity determined with use of this trajectory is in good agreement with the value 1258 m s^{-1} measured with use of the frame-target device.

By analyzing the signals of pressure gauges recorded in the firing T-64 (Figure 8) with the traveling charge including the pellets of SFNC, one can notice that the specific peak generated by the fast burning of the SFNC at the signal of the breech gauge is reproduced by almost identical peaks at the other pressure gauges placed along the barrel. In summary, a unique wave pattern formed which is presented in Figure 12, together with the projectile trajectory. As obvious, the pressure wave arises just near the projectile and runs in direction to the breech at a velocity of ca. 1 km s^{-1}. After refraction from the breech face, the wave propagates in the opposite direction, and its velocity increases due to the co-current gas flow. The place of the wave origin (distance 0.65 m and time 1.5 ms) indicates that the traveling charge burning continues behind the

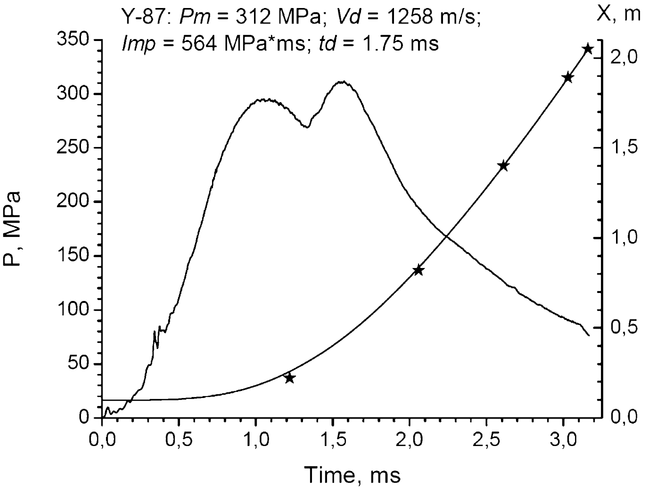

Figure 11. Calculated trajectory of the projectile moving along the barrel for the shot Y-87 with the top-ignited traveling charge (corresponding to the right axis) and experimental points of the time markers labeled by the stars. $V_d = 1258\ \mathrm{m\,s^{-1}}$.

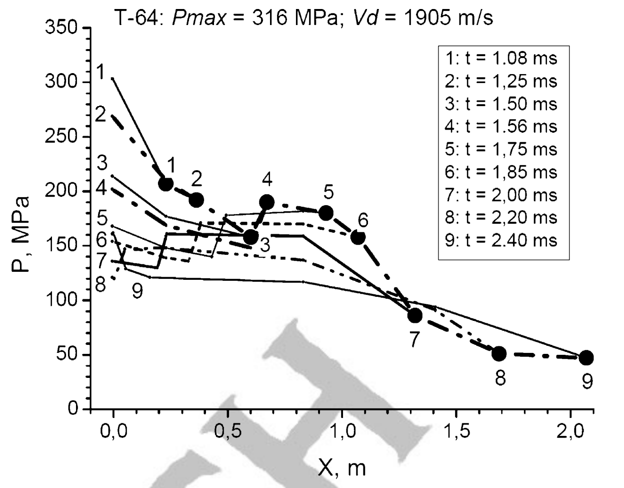

Figure 13. Evolution of the spatial pressure profiles in area behind the projectile. Firing T-64. (1)–(9): serial time instants. Circle points belong to the projectile in various time instants.

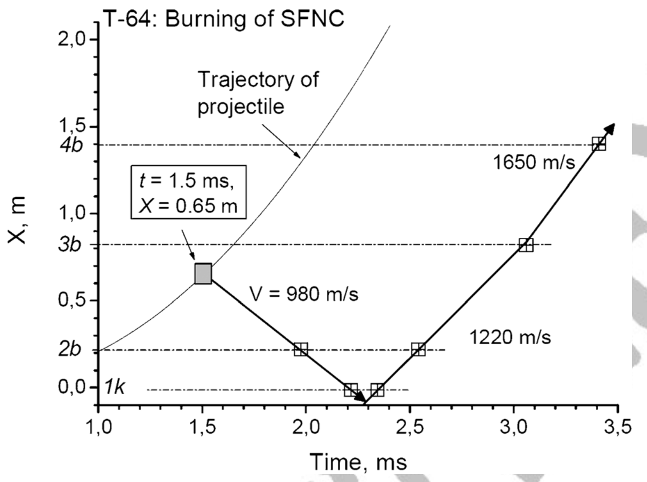

Figure 12. Trajectory of propagation of the pressure wave generated in the area behind projectile due to the fast burning of the SNCF pellet. Dotted straight lines are positions of pressure gauges.

pressure maximum on the descending section of the pressure diagram.

A particularly interesting plot is shown in Figure 13. There are the spatial pressure profiles in different time instants, drawn relying upon the pressure diagrams along the barrel recorded in the firing T-64. Note, that in the case of the conventional charge the identical pressure profiles drawn in space behind the moving projectile look like a set of almost straight lines monotonically decreasing from the maximum value, which takes place in the breech to the pressure value at the projectile back. The three first profiles in Figure 13 which correspond to time instants up to 1.5 ms demonstrate just the same behavior. However, after that time the pressure profiles are dramatically transformed, and the plateau-like or upward convex sections appear. Moreover, during some time (profiles 5 and 6) pressure at the projectile base turns out to be even higher than pressure in the breech.

4 Brief Discussion

The research described herein has shown that the block charges of CMPC type have good prospects for application as the traveling charge to increase ballistic performance. CMPC maintains its integrity in course of movement along the barrel; its ignition is completed after the point of the maximum pressure on the descending section of the pressure diagram. Significant increment of the muzzle velocity compared to the charges of conventional scheme composed of the 7-perforated grained propellant was obtained for two different masses of the projectile, which differ by three times. Evidently, the possibility of a further increase of the muzzle velocity exists due to optimization of the charge properties. Reservations concern a few factors. One of them is the burning rate of the propellant grains forming the traveling charge; this rate, when the propellant VTM was used for the traveling charge, seems to be insufficient. Increase of the burning intensity (per unit volume) due to partial replacement of the VTM propellant by the thin-web VU propellant in a pellet of the traveling charge gave a positive effect in the firing series with the heavy 104-g projectile. This effect manifested itself in transformation of the breech pressure diagram and the muzzle velocity increment. However, the same replacement in the firings with the light projectile turned out to be ineffective, maybe, owing to the shorter shot travel time. And only the partial substitution of the porous SFNC grains produced the expected effect.

The application of the porous grains of SFNC propellant in the traveling charge is a good example of efficiency of the polymer coating of the propellant grains. The PVB film gives regular behavior to burning of the porous propellant, which in original state (with no film) demonstrates a strongly pronounced propensity to the explosive development. That is the positive effect, as we believe, missed by the American scientists in their research with VHBR compositions as the traveling charge, which had finished unfortunately [6].

5 Conclusions

CMPC could be manifested as the traveling charge in the hybrid scheme and can be recommended as a promising means for enhancement of the muzzle velocity.

(i) It is shown experimentally that the traveling charge ignites over its total length and burns up behind the point of maximum pressure. The descending section of the breech pressure diagram is transformed; one can see sections of upwards convex, or sections with plateau or secondary peak.
(ii) The shape of the spatial pressure profiles behind the accelerating projectile also changes; and pressure at the projectile base can be even higher than pressure in the breech for some time interval.
(iii) All these properties result in increasing muzzle velocity, partially due to the possibility to burn more propellant with no increase of the maximum pressure.
(iv) The largest increment of the muzzle velocity in the 23-mm smoothbore laboratory gun, in comparison with the charges of conventional scheme is of 340 m s^{-1} or 23 % for the light 35-g projectile and 200 m s^{-1} or 19 % for the heavy 104-g projectile.

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FULL PAPERS

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Compacted Modified Propellant Blocks as Traveling Charge in the Hybrid Shot Scheme