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STUDIES AND RESEARCHES REGARDING THE LIQUID PROPELLANT BALLISTIC SYSTEMS

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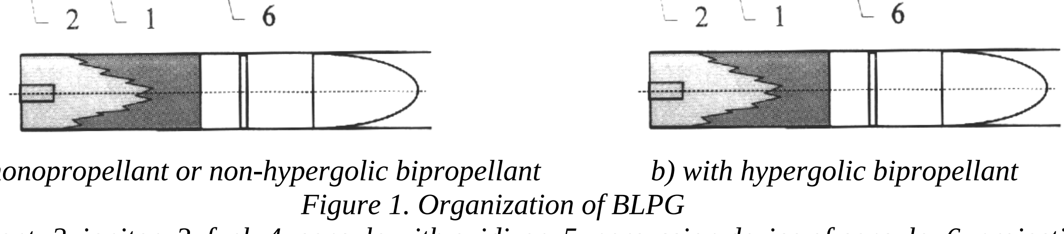
ABSTRACT
In this paper are presented some aspects concerning the interior ballistics of the liquid propellant ballistic systems. The mathematical model for such ballistic system is obtained. On the bases of this mathematical model was realized an interior ballistics software. With the aid of this mathematical model were established the main ballistic characteristics for a new liquid propellant ballistic system, by numerical simulation. The values of main ballistic magnitudes of this new liquid propellant ballistic system are compared with values of similarly characteristics from specialty literature.
Keywords*:* ballistic system, interior ballistics software, liquid propellant (LP).

1. INTRODUCTION

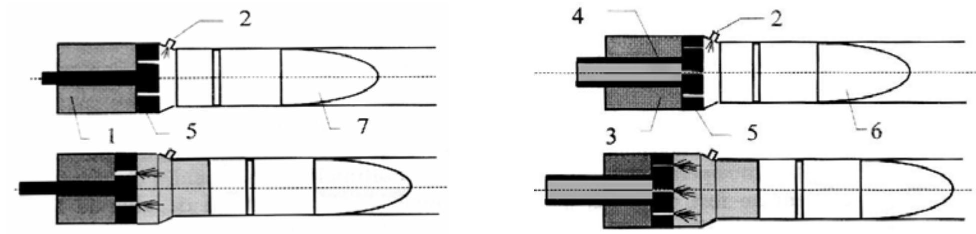
Were created many models of liquid propellant gun (LPG) and were used some types of liquid propellants, but not was realized a good control of combustion and ballistic reproducibility. It must to remark that after 1994 LPG come back in actuality due to elaborating of two concepts regarding the geometry of combustion chamber. One of them is referred to the chamber in steps and another at segmented chamber, both concepts following the control of combustion and ballistic reproducibility. The utilized liquid propellants in guns are divided in two groups [1]: *monopropellants* (*monoergols*), consisting of one component (simple) or a homogeneous mixture of two or many components (complex); *bipropellants* (*diergols*), consisting of two components, a fuel and an oxidizer, which are stored separately. The bipropellants can be either hypergolic or non-hypergolic. In case of hypergolic bipropellants the combustion occurs only when both components come in contact. In case of non-hypergolic bipropellants, as well as monopropellants, is necessary to exist an external igniter, electrical or pyrotechnic. The monopropellants are stabile substances, which has a specific energy greater than solid propellants. An essential disadvantage of the monopropellants consists in great of their sensibility concerning the powerful sources of firing. Until the present all created variants of liquid propellant guns can be divided in two groups [2]: *Bulk-Loaded Propellant Guns* (BLPG), in which the combustion chamber is reservoir and is filed with liquid propellant before firing (Fig. 1); *Liquid Propellant Guns with Injection* that can be external and regenerative (RLPG). In case of the guns with injection, the propellant is pumped during of firing from reservoir in the combustion chamber. The guns with external injection need an external source of high pressure, so that this system is not utilized in military applications. The system with regenerative injection uses the pressure from combustion chamber, which is amplified and applied propellant from reservoir by a piston with differential area (Fig. 2).



a) with monopropellant or non-hypergolic bipropellant *b) with hypergolic bipropellant*

Figure 1. Organization of BLPG

1. propelant; 2. igniter; 3. fuel; 4. capsule with oxidizer; 5. percussion device of capsule; 6. projectile.



a) with monopropellant *b) with bipropellant (non-hypergolic or hypergolic)*

Figure 2. Organization of RLPG

1. monopropellant; 2. igniter; 3. fuel; 4. oxidizer; 5 differential piston; 6. projectile.

The liquid propellant guns are more complex than conventional guns (with solid propellant), but present some advantages, such as [3], [5]: the ballistic performances of LPG are with approximately 20% better than conventional guns (X=40km with classic projectile, X=50km for base-bleed projectile, in the case of howitzer caliber 155mm); the firing cadences with these guns will be more great, because the using liquid propellants facilitates complete automation of firing operations (approximately 12 rounds/ minute, in lapse of time of 5minutes); the cost prices on round will be more reduced with approximately 20% in case of liquid propellants; the prolongation of barrel life due to a temperature more low with 500K in case of combustion of liquid propellants in guns; the reduction of artillery pieces on battle file due to the increased ballistic performances and the more great firing cadences; the possibility of increasing unit of fire of these artillery systems, especially for the guns mounted on battle machines; the facilitation of logistics in case of these guns. The principle working of RLPG that is presented in Fig. 3 is following [2]:

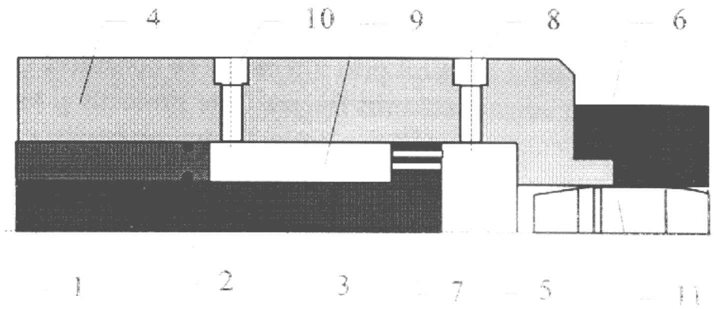


Figure3 RLPG with simple in-line piston

1. breech plug; 2. seals; 3. regenerative piston; 4. chamber; 5. combustion chamber; 6. barrel; 7. injection orifices; 8 – igniter port; 9. reservoir chamber; 10. propellant fill port; 11. projectile.

the volume of the reservoir chamber (9) can be modified by the displacement of the breech (1); the monopropellant is pumped into the reservoir chamber through the fill port (10) from chamber (4); the injection orifices (7) are closed at the beginning, in order to prevent the flow of the LP into the combustion chamber (5); the hot gas produced by the igniter that is located in the igniter port (8), acts on the differential piston (3) and compresses the LP into the reservoir chamber; the pressure into the reservoir chamber is greater than the pressure into the combustion chamber because the inner area of the differential piston is smaller than its outer area; the injection of LP through the injection orifices (7) starts when the pressure into the combustion chamber reached a certain value, named initial injection pressure (approximately 4 MPa); the injected LP is initiated by the hot gas of the igniter and burns increasing the pressure into the combustion chamber; the projectile starts to move when the pressure into the combustion chamber reaches the start pressure (approximately 30 MPa).

2. MATHEMATICAL MODEL OF BALLISTIC CYCLE

Taking into account the complexity of ballistic cycle with these guns, for elaborating of mathematical model was adopted followings hypotheses [6]: the entire mass of injected LP at the moment into the combustion chamber burns instantaneously, releasing whole its energy; the discharge coefficient of injected LP into the combustion chamber from the reservoir chamber has got a constant value; the lost energy at friction between projectile and barrel and between piston and chamber is considered as a fraction of projectile energy and piston energy respectively; the lost heat to the gun barrel is considered as a fraction of total propellant energy; the LP injection starts when the pressure of the generated gas by igniter reaches a certain value; the projectile begins to move when the pressure of gas reaches the value of start pressure; the mass flow of gas produces by igniter is considered constant; the LP fills completely the volume of reservoir, the losses due to the gas-tight elements are neglected. The differential equation of pressure into the combustion chamber is:

$$\frac{dP_c}{dt} = (1 - H_b)\left[\frac{F}{U_c}\left(\frac{dm}{dt} - \frac{m}{U_c}\frac{dU_c}{dt}\right) + \frac{F_i}{U_c}\left(\frac{dm_i}{dt} - \frac{m_i}{U_c}\frac{dU_c}{dt}\right)\right] - \frac{m_z(\gamma-1)(1+f_z)}{2U_c}$$

$$\left(2V_z\frac{dV_z}{dt} - \frac{V_z^2}{U_c}\frac{dU_c}{dt}\right) - \frac{m_p(\gamma-1)(1+f_p)}{2U_c}\left(2V_p\frac{dV_p}{dt} - \frac{V_p^2}{U_c}\frac{dU_c}{dt}\right). \quad (1)$$

The pressure into the reservoir chamber is obtained from Tait's equation, adapted for LP [4]

$$\frac{dP_r}{dt} = \frac{\beta}{\rho_0}\frac{d\rho}{dt}. \quad (2)$$

where $\beta = A + BP_r$ [5].

The density of LP into the reservoir chamber is obtained from equation of mass conservation, thus:

$$\frac{d\rho}{dt} = -\frac{\rho}{U_r}\frac{dU_r}{dt} - \frac{1}{U_r}\frac{dm}{dt}. \quad (3)$$

The mass flow of injected LP into the combustion chamber is given by

$$\frac{dm}{dt} = C_d A_j \sqrt{2\rho(P_r - P_c)}, \quad (4)$$

The motion of piston is expressed by the following equations:

$$\frac{dV_z}{dt} = \frac{1}{m_z}\left[P_c(A_z - A_j) - P_r(A_r - A_j)\right]; \quad (5)$$

$$\frac{dz}{dt} = V_z. \quad (6)$$

The equations that characterizes the motion of projectile have following form:

$$\frac{dV_p}{dt} = \frac{P_c A_p}{m_p}; \quad (7)$$

$$\frac{dx}{dt} = V_p. \quad (8)$$

The variation of the volume of combustion chamber depends of the projectile and piston displacement and is given by relation

$$\frac{dU_c}{dt} = V_z A_z + V_p A_p. \quad (9)$$

The variation of the volume of reservoir chamber, similarly, is expressed with the aid of relation

$$\frac{dU_r}{dt} = -V_z A_z. \quad (10)$$

The mass flow of igniter propellant is given by

$$\frac{dm_i}{dt} = r. \quad (11)$$

The equations (1)-(11) form the mathematical model of ballistic cycle with regenerative liquid propellant guns with simple in-line piston. The interior ballistic software was elaborated on the basis of this mathematical model and was validated for a RLPG 30 mm caliber with the length of barrel 2.6 m, the mass of projectile 0.360 kg the mass of monopropellant LP 1846 charge 0.250 kg [6].

3. ESTABLISHING OF DESIGN PARAMETERS

The establishing of main design parameters was realised by numerical simulation. During of the numerical simulation were modified the following design parameters: the diameter of combustion chamber, D_c; the diameter of piston shaft, d_s; the number of the vents, N_v; the mass of propellant charge, m; the volume of combustion chamber, U_c. The interior ballistics software allows to study the influence of the variation of these designed parameters over the following ballistic characteristics:

the muzzle projectile velocity, v_g; the kinetic energy, E_g; the maximum pressure into chamber, $p_{max.c}$; the maximum pressure into reservoir, $p_{max.r}$; the shot out time, t_g; the shot out pressure, p_g; the ballistic efficiency[1], r_g; the piezometric efficiency[2], η_g; the burnt propellant, m. With the aid of interior ballistics software were obtained the curves of variation of these ballistic characteristics versus named design parameters. From these curves can be find these values of chosen design parameters for which the ballistic characteristics have got suitable values, without the exceeding of the imposed design parameters values.

4. RESULTS AND CONCLUSIONS

Using interior ballistics software, were determined the values of chosen design parameters for that the main ballistic characteristics get maximum or near maximum values, in the case of a new RLPG 35 mm caliber with the length of barrel 3 m, the mass of. projectile 0.360 kg, the maximum pressure into reservoir 320 MPa. The obtained values of these parameters with the aid of numerical simulation are following: the diameter of the combustion chamber, D_c=55 mm; the diameter of the piston shaft, d_s=24 mm; the number of vents, N_v=24; the mass of propellant charge, m=0.440 kg; the volume of the combustion chamber, U_c=45 cm^3. In the case of a RLPG 35 mm caliber which has got these design parameters, the main ballistic characteristics are following: the maximum pressure into reservoir, $p_{max.r}$=316.9 MPa; the maximum pressure into combustion chamber, $p_{max.c}$=263.6 MPa; the muzzle projectile velocity, v_g=1256.5 m/s; the shot out time, t_g=5.26 ms; the shot out pressure, p_g=13.7 MPa; the piezometric efficiency, η_g=53.8%; the ballistic efficiency, r_g=30.5%; the kinetic energy of the projectile, E_g=483.9 kJ. For this RLPG 35 mm caliber, in Figure 4 and Figure 5 it is presented the variation of the pressure into reservoir and into combustion chamber as well as of the projectile and piston velocity versus time.

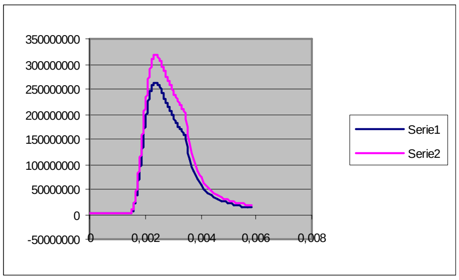


Fig. 4. The variation of pressure versus time

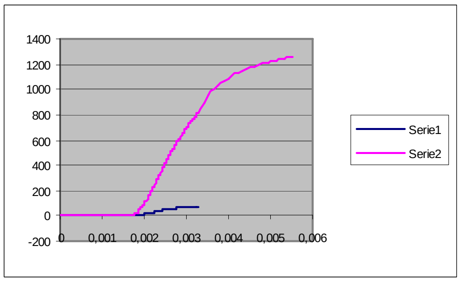


Fig. 5. Variation of velocity versus time

5. REFERENCES

[1] CHRIS, JENKINS, "Monoergols and Diergols-The Way Forward for Projectiles", MILTECH 7/88.
[2] KLINGENBERG, G., JOHN, D. KNAPTON, Liquid Propellant Gun Technology, Vol. 175 Progress in Astronautics and Aeronautics, Paul Zarchan, Editor-in-Chief, 1998.
[3] BIRK, A., REEVES, P., Annular Liquid Propellant Jets: Injection, Atomization and Ignition, BRL-TR-2780, 1987.
[4] WALTER, F. MORRISON; JOHN, D. KNAPTON, Gun Propulsion Technology, Vol. 109, Progress in Astronautics and Aeronautics Edited by Ludwig Stiefel, 1988, pp 413-471.
[5] PAGAN, GORDON, DAVID, C. A., Regenerative Liquid Propellant Gun Modeling, Proc. of Seventh Symposium on Ballistics, Apr. 1983.
[6] DHAMI, G.S., TATAKE, K.J., Modeling a Regenerative Liquid Propellant Gun, Def. Sci. J. 45/2,1995, pp 161-171.

[1] defined as the ratio between the shot out kinetic energy of the grenade and the total energy of the LP;
[2] defined as the ratio between the mean pressure that acts on the grenade in the launcher and the maximum.