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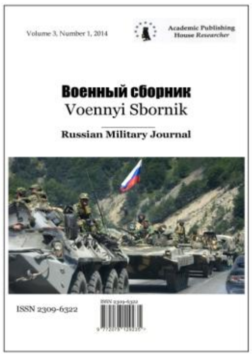

UDC 93

An Estimation of the Pneumatic Gun's Effectiveness

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Abstract. The paper presents a critical analysis of 19th Century pneumatic naval guns, based on a simple simulated model. Based on documentation available, the authors were able to ascertain the parameters that could be used to characterize the effectiveness of the pneumatic guns. In the process, some errors in previous literature were found.

Keywords: Naval History, USA, Pneumatic Gun, Historical Reconstruction, Mathematical Modeling.

At the end of 19th century, the armies and navies of several nations were experimenting with some systems of the pneumatic guns, which launched projectiles filled with dynamite. But the information about these guns contains many discrepancies, though the weapon's effectiveness was questioned. For example, Schroeder, writing in 1894 [see Bibliography], doubted the effectiveness for a number of subjective reasons. But Watson, writing in 1991, cites objective reasons for the weapon's failure. In an effort to arrive at an objective scientific conclusion, a simulation model program was created.

1. Describing of the model

The model consists of two components: internal and external ballistics. The first part is the gas-dynamic task. Its calculation scheme is the interplay of two fundamental components; the volume of the compressed air tank, and the volume of the chamber of the gun. The latter will increase as the projectile is propelled down the gun tube towards the muzzle. A simple schematic of gun's pneumatic-system is shown in the Fig. 1.

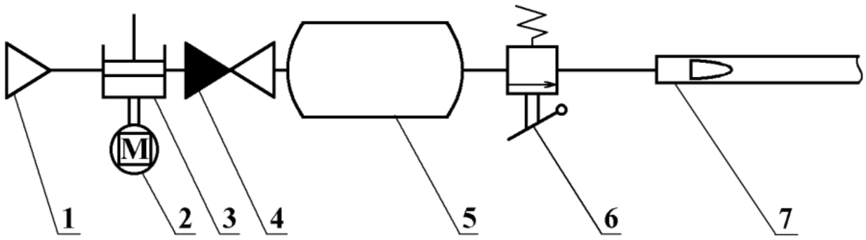

Fig. 1. The principal gun's pneuma-schematic: 1 - collector; 2 - compressor's drive; 3 - compressor; 4 - return valve; 5 - gas-reservoir; 6 - main valve; 7 – gun tube

The gas's outflow *G* from high-pressure balloon is over-critical only:

$$G = p_1 F_k \sqrt{\frac{k}{RT}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}},$$

where p_1 – gas pressure in tank; F_k – the critical section of the main valve; k – the adiabatic index of the air; RT – the "powder's power", on this case power of the compressed air.

The gas pressure gives the acceleration to projectile during the travel through the gun tube, which at the muzzle yields the initial, or muzzle, velocity. That movement in the tube is the parameter of the interior ballistics component.

The mathematical model of this first component is contained in two differential equation: the equations of the law of the impulse preservation for the projectile in gun tube, and the equation of indissoluble (Law of Lomonosov – Low of the matter preservation) for the gas in the tank.

$$\frac{dm_b}{dt} = -G,$$

$$\frac{dv}{dt} = \frac{(p_2 - p_h)F}{m} - g(\sin\alpha - f\cos\alpha);$$

where m_b – the mass of gas in the tank; v – the projectile velocity; m – the projectile mass; p_2 – the air pressure in gun tube; p_h – the air pressure of the atmosphere; F – frontal area of projectile; g – gravity [9.81 m/s squared]; f – the index of friction (projectile and gun tube).

To this equation is added some algebraic equations:

$$p_1 = \frac{m_b RT}{V_b},$$

$$p_2 = \frac{(m_0 + \Delta m)RT}{V_g},$$

$$V_g = F\int v\,dt.$$

V_b – the volume of the air tank; V_g – the internal volume of the gun tube; m_0 – the initial mass of the air in the gun tube; Δm – the mass of the air released from the tank.

The equations of the second component of the mathematical model are very trivial, and are in every manual of exterior ballistics. The A.A. Dmitrievsky edition, for example, presents four differential equations and some algebraic equations to solve the exterior ballistics problem.

So, the model is complete and mathematically valid, only needing initial data for calculations. And for this, Patrick McSherry provided the research.

The initial pressure in the compressed air tank was about 70.5 atm. But the information about tank's volume is very interesting. Seaton Shroeder, the first commander of cruiser *Vesuvius*, which mounted three 381-mm [15-in] pneumatic guns, wrote: the "volume of tank is 276 sq feet" (7.83 m^3). But in his book, Shroeder wrote: "It's interesting, but the mass of the air in the tank is about three tons – this is result of displacement augmentation…before and after filling the tank".

If the condition of gas is normal (temperature about 300 K), the equation of Mendeleev-Klapeiron gives the tank a volume of 48 m³. So, every gun had two tanks. It seems logical; one tank plumbed for the firing of the gun – the 'propellant charge' as it were -- and the second is connected to the compressor.

The interior ballistics component gave some interesting results (Fig. 2). Curves 1 and 2 show the normal changes of acceleration in the ordinary firing guns. If the velocity of combustion of the propellant is decreased, say by increasing the propellant powder grain size or form, the point of maximum acceleration occurs later and will be lower. Thus the difference between curve 1 and curve 2. But it turned out that the interior ballistics of pneumatic guns is very different!

Writing in 1993, M.C. West asserts that the air pressure in gun tube remains constant, and as a result of this, the acceleration is increased constantly for the length of the gun tube (curve 3b). But this is mistake! The assumption behind 3b can only be valid for a very great tank volume, and a large aperture diameter of main valve, providing a continuous flow of compressed air, which is not the case. Really, this is asymptotic assumption, and the more valid assumption is better reflected by curve 3a. It is similar to the curve for slow-burning powder. The maximum of pressure will be strongly pronounced, because the time the valve is open is small, anti-pressure is small too, and the consumption of compressed air is great. But with time, the anti-pressure will increase, and the compressed air consumption will decrease as the supply in the small tank used for 'firing' the gun is expended and the valve closed. So, if we have the extreme of pressure, then we also have the extreme of acceleration. From the point in time, represented by live T3, the valve is closed and no more compressed air enters the gun tube, so the force continuing to push the projectile is from the expansion of compressed gasses that is similar adiabatic law.

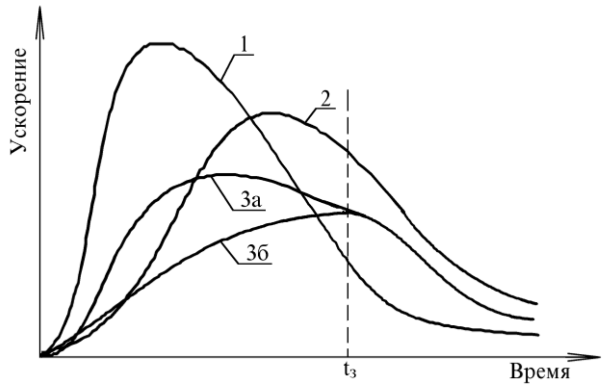

Fig 2. Projectile acceleration in the gun

The form of projectiles is very difficult to quantify. Theoretical determination of resistance law is very hard, as it had a very non-standard shape and inordinate length, so the existing methods for the determination of the form factor seem inapplicable. But, according to Shroeder, the projectile had a form factor using the Mayevskiy law of about 5.646. For the air resistance for the external ballistic component of the model, the superior Siacci law was used. So the form factor using Siacci law is about 5.06. The atmospheric condition used was the "Standard Atmosphere" (See GOST 4401-81).

2. The discussion of results

One of the complex criteria for estimating a projectile's ballistic characteristics can be served by the thickness of armour that a hypothetical AP shell can perforate. As can be seen in the graph (fig. 3), the curve for a Zalinsky-type projectile is "non-standard." For traditional artillery, armour penetration decreases as the distance increase. But for the pneumatic gun penetration increases. The "sawtooth" character of the curve for the Zalinsky projectiles is due to the necessity of using lighter projectiles to obtain longer ranges, see Tables below. *Vesuvius* used tables to estimate the maximum range for each weight of shell. The fixed elevation, coupled with the necessity to use lighter shells for longer ranges, effectively limits attack on armour to a small zone at the maximum range for each weight of projectile, reflected in Fig. 3 as the points in the "sawtooth" curve. Thus, unlike traditional artillery projectiles which would have an effect at any point along the trajectory, for the pneumatic shell, attack on armour would be limited to a few spots at range. At the usual combat range of about 2…3 kms, the effect on armour of a pneumatic shell is commensurable with shells Mk III (102/40) and Mk II (127/40) guns of the American fleet. Though this comparison, certainly, is speculative sense, as the high-explosive effect of the dynamite shell, in any case, would be more damaging than ordinary armour penetration.

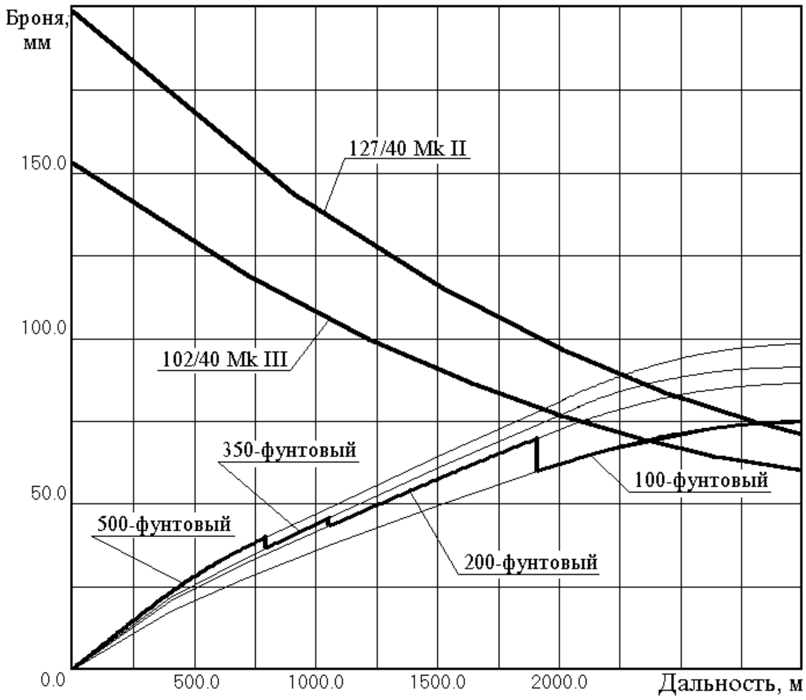

Fig. 3. Comparative perforate armour of the 127-mm, 102-mm shells and hypothetical armour piercing shell of a pneumatic gun

The simulation model revealed a “draw-down” effect in the pneumatic system, caused by continuous use. Bearing in mind that the main compressed air storage tank had to service three of the pneumatic guns, a decline of air pressure was inevitable, with a negative effect on shooting to range. This is best illustrated by simplifying the process to a single gun, shooting 200-pound [weight of explosive; 500 lb projectile weight] shell. For the first shot (muzzle velocity 204 m/s, the range 1880 m) pressure in the tank falls to 68.08 atm. So at the second shot and further these parameters are following:

2-nd	68.02 atm	198 m/s	1780 m
3-rd	65.73 atm	194 m/s	1700 m
4-th	63.55 atm	188 m/s	1600 m
5-th	61.50 atm	185 m/s	1550 m
6-th	59.52 atm	180 m/s	1470 m.

Thus, without recharging, the sixth shot range falls about a quarter. By the way, Shroeder tried to estimate fall of pressure after the first shot, using the law Boil-Mariott; increase of gas volume he has estimated as: 0.08 m^3 – the volume of various internal cavities and 1.40 m^3 – 3/4 volumes of the gun. Thus, there was the 59 atm [70.5 - 7.8 / (7.8 + 0.08 + 1.4) = 59 atm] remaining.

The simulation model also allows an estimate of the tolerance in operation of the valve. As has shown testing, the time of valve open-shut operation is ideally 0.2 sec. It is interesting that if the tolerance of operation is off by 0.001 sec, the change of range is about 10 m, plus or minus. For engineering of that time such of the tolerance was very good, but for the grouping of shots it was obviously unsatisfactory. In this connection, the mediosquare deviation of shells was almost in some tens greater than traditional guns. By the results of May 1891 firing trials, intended to calibrate a single projectile weight, three shells were fired. The second landed about 50 yards short of the first, and the third about 50 yards over. So the probability of hitting a target was low.

And finally, probably most essential shortcoming as a naval weapon, as mounted in *Vesuvius*, is its lack of range. In the literature there is no information on the maximum range, but most likely it was no more than 3 kms. The usual combat distance at the time was about a mile. Besides, because of its low velocity, the shell was rather a long time in flight. The simulation model gives the following interesting results for an estimation flying time:

Range, m.	700	1000	1400
Time, sec.	6.4	7.7	9.2

At such flight times, the target not only could to see a shell, but depart!

A unique way to radically increase muzzle velocity was to increase of pressure in entire system. According to A. Yakimovich, in a folder there were items of information that there was design development of a pneumatic gun with pressure of compressed air about 350 atm. But if the tolerance of the valve operation of this gun also was 0.001 sec, than the change of range turns out 40 m! From here it is clear why that the gun design was not pursued farther than the drawings.

Also there is information that ostensibly "the experiments with 600-pound (272-kg) dynamite charges" were carried out. In this case the shell weighed 680 kg (1500 pound) and had length 2.1 м (7 feet). In the literature there is no information on its range, it is underlined only, that it was less than mile. The simulation model demonstrates why a shell of this type was not used. In a gun it could be launched only up to a velocity of about 100 m/s, and thus, the range would be hardly 500 m. At such range the firing ship itself could be damaged from the explosion of the shell!

The developed simulation model allows us to estimate the various factors of combat efficiency of pneumatic guns, that, for example, was made by the author in work for 267-mm of the pneumatic gun of the Brazilian cruiser *Nictheroy*. The basic data on this system are taken from A. Saks work, and applied to the 381-mm gun of the cruiser *Vesuvius*.

The comparative characteristics of the dynamite guns

System	203-mm	267-mm		381-mm of cruiser "Vezuvius"			
Length of tube, m / feet	18 / 60	16,47 / 54		16,47 / 54			
Pressure, ath.	70.5	70.5		70.5			
Mass of explosive, kg	45.3	91	22.6	227	159	91	45
pound	100	200	50	500	350	200	100
Mass of shell, kg	62	158	91	445	350	227	130
pound	137	348	200**	980**	780**	500	285**
Shell's kaliber, mm	203	267	267	381	381	381	381
Muzzle velocity, m/s	230*	160*	230*	130*	150*	200	290*
Range, m	2100*	1200*	2100*	760*	1100*	1900	3000*

System	381-mm coastal gun					381-mm
Length of tube, m / feet	15 / 50					15 / 50
Pressure, ath.	140					350
Mass of explosive, kg	227	181	136	91	45	91
pound	500	400	300	200	100	200
Mass of shell, kg	448	390	330	252	195	227
pound	990	860	728	558	430	500
Shell's kaliber, mm	381	381	381	381	381	381
Muzzle velocity, m/s	210*	230*	260*	300*	350*	520*
Range, m	1900*	2100*	2400*	3000*	3200*	4500*

Note: * – account; ** – is chosen in a proportion to the nearest analogue. Pneumoautomatics for all guns is taken, as for guns *Vezuvius*. The eminence angle of guns in all cases is 18°.

Also results of accounts for 381-mm of the coastal gun is interestingly. Work by V.G. Malikov contains the information, that the 227-kg shell flayed on range 1800 m (calculated data has given similar figure – see table), whereas the 51-kg shell on 5000 m. This last, however, appears exaggerated.

Conclusion

The history of creation and combat using of pneumatic artillery is very instructive. All its defects are objective, and caused by the low level of technical development of 19th century. But with our modern technology, the idea of pneumatic guns is very attractive. There are some advantages over traditional firing guns: noiseless, the ability to fire a shot in the every condition (even from under water!). And such a weapon would be useful in, say, anti-terrorists action.

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