STUDY ON THE INFLUENCE OF THE NOZZLE PROFILE ON THE RECOILLESS CONDITION OF THE RECOILLESS GUN

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ABSTRACT

In this paper, a mathematical model was built to determine the recoilless condition of the recoilless gun according to the structural parameters of the nozzle. The investigation of the recoilless condition of the artillery is carried out when changing the diameter of the critical section d_{th} and the section at the outlet of the nozzle d_a. Numerical calculation applied on recoilless gun DKZ-82mm. The calculation result is the law of the recoil force R according to d_{th} and d_a. This result is the theoretical basis to determine the critical cross-sectional diameter and the diameter at the outlet of the nozzle to ensure no recoilless condition for the gun.

Keywords: *Nozzle, recoilless condition, recoilless gun.*

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1. INTRODUCTION

Shots made on conventional artillery often have a large recoil force. For the artillery rack to withstand large loads, the artillery rack is usually designed to be durable, and heavy and add its recoil brake device [1]. Therefore, large-caliber artillery is often bulky and heavy. A new direction in the development of artillery is the introduction of artillery guns according to the principle of jet kinematics, also known as recoilless artillery guns. The recoilless gun is a type of artillery weapon of the jet kinematics system, in which the recoil force is eliminated by a kinematic balance between the forces acting on the barrel when firing. The jet kinematic system is a system in which the bullet velocity is provided by the propellant gas energy that burns in the barrel when simultaneously ejecting from the tail of the barrel to ensure its non-recoil [2-5].

Some characteristics of using recoilless artillery are as follows [6]:

- Has relatively large power while the weight of the carriage is small;

- Has a simple and light structure suitable for infantry equipment. Due to its small weight and simple structure, it is convenient for maneuverable porters and infantry reinforcements through complex terrain. Since the discovery of the steel penetration ability of concave shells, recoilless artillery has become an important anti-tank weapon.

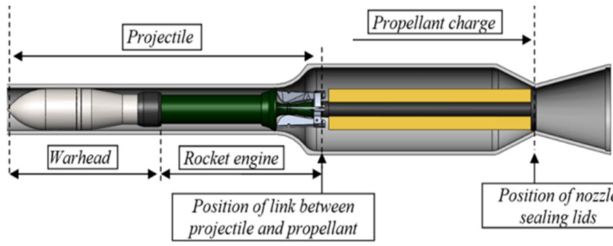

Fig. 1. The general structure of the recoilless gun

- Because there is no recoil force, the artillery does not need to have a recoil brake device like conventional artillery guns or have support like a mortar, and now the artillery rack only acts as a directional platform to support the barrel and for mounting other structures;

- The biggest structural difference between recoilless artillery and conventional artillery is the nozzle system at the rear of the recoilless artillery. This nozzle makes the gas flow after a large speed, the jet force is generated to eliminate the recoil force of the artillery. Therefore, it is important to study and understand the influence of the nozzle profile on the recoilless condition of the recoilless artillery.

In the world, there have been many studies on recoilless guns. Some studies have proposed specific theories on the problem of interior ballistics of recoilless artillery guns [7-12], and some studies have carried out testing the pressure in the combustion chamber to determine the interior ballistics characteristics of a recoilless gun, thereby determining the recoilless condition of the gun [9-15]. However, there has been no research on the influence of structural characteristics of the nozzle on the working conditions of recoilless guns.

In this study, the author focuses on analyzing in detail the impact of the nozzle profile on the recoilless condition of recoilless artillery, providing the necessary information for the development and optimization of artillery design technology. By further studying the influence of the nozzle profile, the improvement of stability, accuracy, and resistance to environmental influences during the use of recoilless artillery is enhanced.

2. THEORETICAL FOUNDATIONS OF BUILDING MATHEMATICAL MODELS

The principle of jet kinematics is applied in most modern anti-tank weapons. The diagram of the jet kinematic system is shown in Fig. 2.

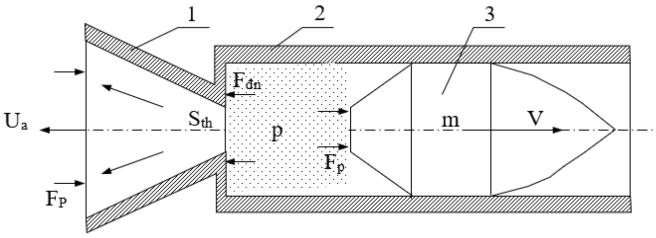

Fig. 2. Diagram of the jet kinematics system

1. Nozzle; 2. Barrel; 3. Projectile; U_a is the exit velocity of the nozzle; S_a is the cross-sectional area of the nozzle exit; S_{th} is the cross-sectional area of the throat; p is the pressure in the barrel; m is the bullet mass; V is the bullet velocity; F_p is the reaction force; F_{dn} is the kinetic force.

If the system has reaction components F_p equal to the kinetic force F_{dn}, it is called a recoilless system. Thus, the load on the rack is reduced, the rack is only a guide and holds the barrel. As a result, the weight of the system is greatly reduced, increasing the metal utilization factor (the ratio of the muzzle energy to the weight of the system).

Based on research results, the system of jet kinematics can be fully or partially balanced. For the jet kinematics system to ensure that the barrel does not recoil, the size of the nozzle and the barrel must have a definite relationship.

2.1. Determine the recoilless condition for the recoil artillery

To establish the problem of recoilless condition for artillery, some assumptions are used as follows [5]:

- The surveyed system only includes barrel - ammunition - propellant - combustible gas.

- Barrel with extended combustion chamber;

- Processes in the barrel are considered stable;

- The propellant is considered to be completely ignited.

2.1.1. Forces acting on the barrel of a jet kinematic system

When the propellant ignites, combustion gas is formed, increasing the pressure and temperature in the combustion chamber. The gas pressure acts on the bullet, imparting kinetic energy to it. On the other hand, the combustion gas pressure also acts on the inner surface of the combustion chamber, barrel, and nozzle causing radial force; axial force, and inertia force.

- The radial force causes stress and deformation on the barrel wall, which in turn affects the durability of the barrel.

- The force of inertia appears on the barrel wall due to the action of the combustion gas pressure.

- The axial force acting on the expanding combustion chamber causes axial stress and deformation in the combustion chamber wall. Therefore, the axial force affects the stability of the gun when firing.

The characteristics of the axial force are as Fig. 3.

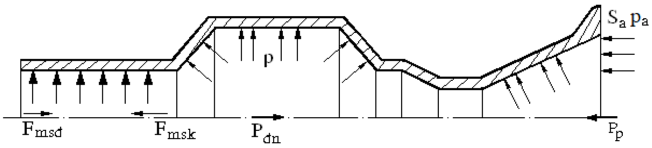

Fig. 3. Diagram of forces acting on the barrel of the jet kinematics system

The diagram shows the barrel of a recoilless artillery with axial forces acting on it. The gas pressure *p* is the variable value acting on the barrel and produces the following axial forces:

a) Kinetic force P_{dn}

Kinetic force or force of gas pressure acting on the bottom of the barrel. This force acts along the barrel axis and causes barrel recoil.

This force is calculated by the formula [1]:

$$P_{dn} = \int_{S_{th}}^{S} pdS \quad (1)$$

This force acts on the inlet cone from the throat cross-section to the barrel cross-section. When calculating, consider that the combustion gas pressure is constant according to the length of the combustion chamber and the inlet cone. That pressure changes significantly only near the critical cross-section. At the outlet section, the pressure of the drug gas changes similar to that in the output section of a jet engine. So, with the assumption that the combustion gas pressure in the combustion chamber of the jet kinematic barrel is constant in length at each time (p = const), the expression for calculating P_{dn} is as follows:

$$P_{dn} = \int_{S_{th}}^{S} pdS = p(S - S_{th}) \quad (2)$$

Thus, the kinetic force of the combustible gas pressure is proportional to the combustible gas pressure and the difference between the barrel cross-sectional area with the critical cross-section. The larger the caliber, the greater the kinetic force P_{dn}. The critical cross-sectional area for a recoilless gun should be calculated from the recoilless condition of the jet kinematics.

b) Components of the jet force P_p

This force is also applied along the barrel axis but in the opposite direction of the dynamic force. The set point of this force is one part to the front bottom, and the other to the barrel.

The component of the jet force P_p is calculated by the formula [1]:

$$P_p = \int_{S_{th}}^{S_a} pdS \quad (3)$$

$$P_p = \int_{S_{th}}^{S_a} pdS = \{\varphi_1\varphi_2[F_r(\xi) - 0.693] - 0.555\}S_{th}p \quad (4)$$

Where:

The function $F_r(\xi) = F_r\left(\frac{d_a}{d_{th}}\right)$ is determined by the table of the ratio of the diameter of the output and the critical cross-section [1].

c) Frictional force of the combustible gas acting on the barrel wall F_{msk}

Hydraulic theory shows that: When the fluid flow moves in the pipe, the friction force is calculated by the formula:

$$F_{msk} = h_f.\Delta p_h.S_e \quad (5)$$

Where: h_f - Friction factor between the combustible gas and the barrel wall; Δp_h - Pressure in the barrel; S_e - Area of effect.

d) Frictional force of the bullet acting on the barrel wall F_{msd}

The friction force of the bullet is calculated by the formula:

$$F_{msd} = f.q \quad (6)$$

Where: q - Weight of the warhead; f - Coefficient of friction.

In practice, F_{msk} and F_{msd} are so small that they can be ignored. Therefore, the barrel balance of the jet kinematic system is based on two fundamental forces: the kinetic force P_{dn} and the reaction force P_p.

2.1.2. Determining the recoilless condition

Equation of conservation of momentum of the system [1]:

$$mdv - \frac{G}{g}U_a dt = p_a S_a dt + Fdt \quad (7)$$

For the system to be in equilibrium, F = 0, and the very small atmospheric pressure component $S_a p_n$ is ignored:

$$P = m\frac{dv}{dt} = \frac{G}{g}U_a + S_a p_a \quad (8)$$

The equation of motion of the bullet:

$$\varphi m\frac{dv}{dt} = p_d S \Rightarrow \varphi P = p_d S \quad (9)$$

Expressions for kinetic force and reaction force components:

$$P_{dn} = p(S - S_{th}) \quad (10)$$

$$P_p = \{\varphi_1\varphi_2[F_r(\xi) - 0.693] - 0.555\}S_{th}p \quad (11)$$

Therefore, the equilibrium condition for the system is determined as follows:

$$P_{dn} = P_p$$

$$P(S - S_{th}) = \{\varphi_1\varphi_2[F_r(\xi) - 0.693] - 0.555\}S_{th}p$$

Divide both sides of the above equation by $p.S_{th}$, we get:

$$\frac{S}{S_{th}} - 1 = \varphi_1\varphi_2[F_r(\xi) - 0.693] - 0.555$$

$$\Rightarrow \frac{S}{S_{th}} - 1 = \varphi_1\varphi_2[F_r(\xi) - 0.693] + 0.445 \quad (12)$$

According to expression (12), the equilibrium condition of the barrel depends on the geometry of the barrel and the nozzle; the stuffing coefficient φ_1, φ_2 the propellant, and other factors expressed in the stuffing condition.

3. CALCULATION RESULTS AND COMMENTS

3.1. Input data

The DKZ-82mm recoilless gun is an 82mm smoothbore recoilless artillery designed and manufactured by the Soviet Union, operating on the principle of jet kinematics, and has been in use since 1954. This artillery is widely used in our army. The parameters of the DKZ-82mm artillery used to determine the recoilless condition of the artillery are shown in Table 1 [13-18].

Table 1. Specifications of the DKZ-82mm gun

Parameters	Symbol	Value	Unit
Diameter of barrel	d	8.2	cm
Diameter of the nozzle's exit	d_a	16	cm
Diameter of nozzle's throat	d_{th}	7.2	cm
Factor taking into account the air flow rate at the nozzle's output cross-section	φ_1	0.93	-
Factor taking into account current constriction at the throat cross-section	φ_2	0.95	-
Ambient pressure	p_n	1.033	kG/cm^2
Ignition pressure of the propellant	$p_0^{+15^0}$	53.5	kG/cm^2
Temperature coefficient	K_t	1.34	

3.2. Calculation results and survey

3.2.1. Investigating the effect of the nozzle's throat diameter

Table 2. Recoil force R respect to d_a

No	d_{th}	$\xi = \frac{d_a}{d_{th}}$	F_r (ξ,k)	F_{dn}	F_p	$R = F_{dn} - F_p$
1	6.734	2.376	1.663	1232.1	770.7	461.4
2	6.834	2.341	1.660	1155.7	786.8	368.9
3	6.934	2.307	1.656	1078.2	800.4	277.8
4	7.034	2.275	1.652	999.6	813.8	185.8
5	7.134	2.243	1.648	919.9	827.0	92.9
6	7.234	2.212	1.644	839.0	839.9	- 0.9
7	7.334	2.182	1.641	757.1	855.3	- 98.2
8	7.434	2.152	1.637	673.9	867.8	- 193.9
9	7.534	2.124	1.633	589.7	880.0	- 290.3
10	7.634	2.096	1.629	504.4	891.9	- 387.5
11	7.734	2.069	1.626	417.9	906.5	- 488.6

To investigate the effect of the nozzle's throat diameter on the recoilless condition of the recoilless gun, the expression $R = F_{dn} - F_p$ is determined. When the value $R \neq 0$, it means that there is a force causing instability to the gun (called the recoil force R); Value $R > 0$, the gun is pushed back; Value $R < 0$, the gun is pushed forward.

From the table of values above, the graph shows the relationship between the nozzle expansion factor ($\xi = \frac{d_a}{d_{th}}$) and the recoil force R when d_{th} changes as follows:

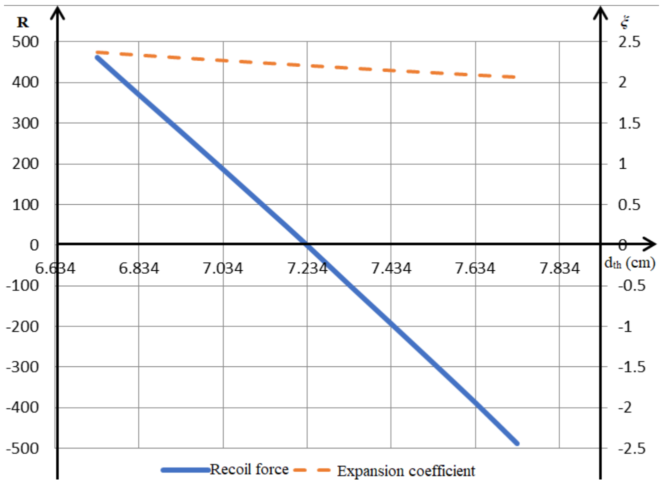

Fig. 4. Graph $\xi(d_{th})$; $R(d_{th})$ respect to d_a

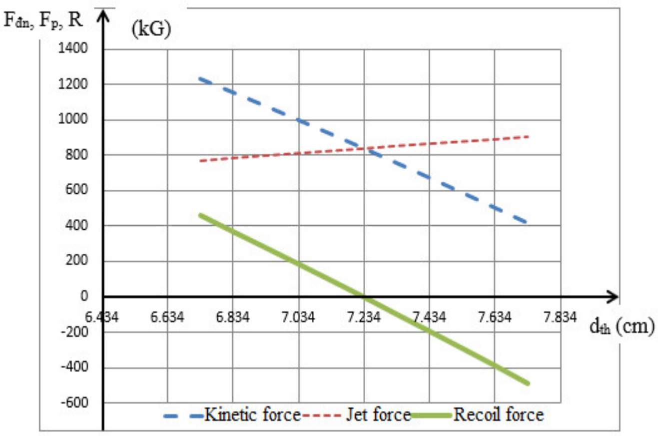

Fig. 5. Graph $F_{dn}(d_{th})$; $F_p(d_{th})$; $R(d_{th})$ respect to d_{th}

Comment:

The graph in Figure 4 shows that: When the throat diameter of the nozzle d_{th} changes (increase or decrease), the expansion coefficient of the nozzle also changes in the inverse direction of d_{th} ie ξ (decrease or increase).

When the critical size of the nozzle d_{th} increases in the upward direction as shown in the graph, initially the recoil force $R > 0$ (the gun moves backward), then the recoil force R decreases to zero (at the time d_{th} = 7.234cm); When d_{th} continues to increase, the recoil force $R < 0$ (the gun moves forward). Thus, for the gun to be stable ($R = 0$) the nozzle must have a defined size (d_{th} = 7.234cm; d_a = 16cm).

Table 2 and Fig. 5 show that:

- When the throat diameter d_{th} increases, the dynamic force F_{dn} also decreases inversely and very quickly (slope of the characteristic curve is large.);

- When the throat diameter d_{th} increases, the reaction component F_p increases proportionally but slowly (the slope of the characteristic curve is small);

- When the throat diameter d_{th} increases, initially the recoil force $R > 0$; then decreases to $R = 0$ and d_{th} continues to increase, the recoil force $R < 0$.

3.2.2. Investigating the influence of the exit diameter of the nozzle

With the input parameters presented in Table 1. The recoil force R is determined when changing the output diameter value of the nozzle around the initial value. The results are presented in the following table:

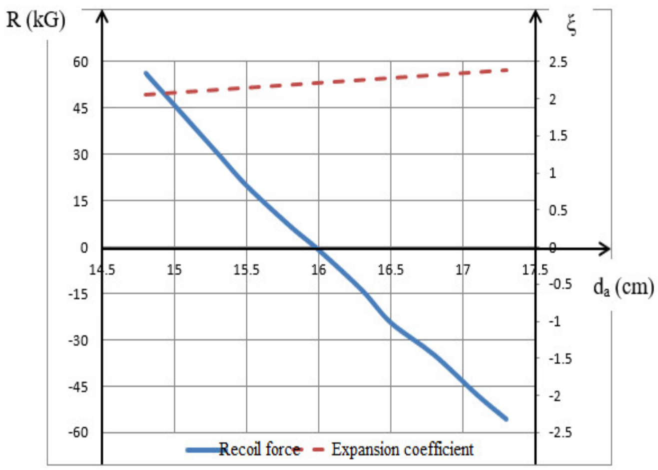

Fig. 6. Graph $\xi(d_a)$; $R(d_a)$ respect to d_a

The graph in Fig. 6 shows that: As the nozzle outlet diameter increases, the expansion coefficient of the nozzle ($\xi = \frac{d_a}{d_{th}}$) also increases. This is what causes the jet force to increase, so the recoil force R is reduced.

Recoil force $R = 0$ when the value d_a = 16cm and d_{th} = 7.2cm. At this d_a value, the gun is the most stable.

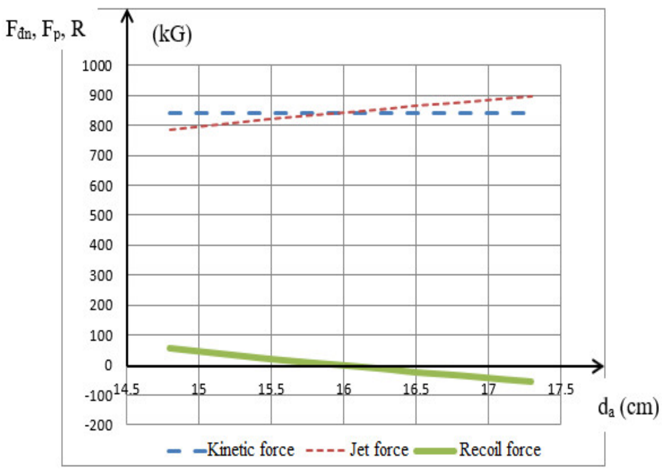

Fig. 7. Graph $F_{dn}(d_a)$; $F_p(d_a)$; $R(d_a)$ respect to d_a

The graph in Fig. 7 shows that:

- When the nozzle outlet diameter d_a is increased, the dynamic force $F_{đn}$ does not change and does not depend on d_a (graph is a horizontal line);

- When the outlet diameter of the nozzle is increased, the reaction component F_p increases proportionally but slowly (the slope of the curve is small).

4. CONCLUSION

In this paper, a mathematical model is established to determine the recoilless condition of a recoilless gun. Based on the theory of this model, the investigation of the influence of the structural parameters of the nozzle on the operation of the gun is carried out. With the obtained results, some conclusions are made as follows:

- The structural characteristics of the nozzle greatly affect the working conditions of the gun, especially the recoilless condition.

- From the calculation results and the above graphs, $F_{dn}(d_{th})$; $F_p(d_{th})$; $R(d_{th})$; $F_{dn}(d_a)$; $F_p(d_a)$; $R(d_a)$, the influence of the throat cross-section and the output cross-section of the nozzle on the gun's stability is very large; However, the effect of the throat cross-section is much larger than that of the output. When changing the throat cross-section of the nozzle by a very small amount (only 0.1cm each time), the recoil force value R changes greatly from a few tens to hundreds of kG/cm^2. When changing the value of the output cross-section (each time changes from 0.2 ÷ 0.3cm), the value of the recoil force R changes only in a much smaller range (a few tens to hundreds of kG/cm^2).

- To increase the service life and prolong the life of the gun, measures to preserve and maintain the recoilless gun must be taken to avoid the influence of external environmental conditions (especially wear of the barrel, worn out nozzle size,…).

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