Analysis of The Projectile Motion was Blocked in Gun Bore

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Abstract. To learn the security of projectile was blocked when high-speed movement in gun bore, interior pressure and the movement of projectile were calculated and analyzed under different postulated conditions. Through the analysis of the change in interior pressure after the projectile, the character of projectile was restricted in gun bore during movement and the pressure on both barrel and projectile, also by these to check security in the design of barrel and projectile, and identified the matching problems which needed careful attention in the design processes of both gun and ammunition.

1. Introduction
The movement of the projectile in the chamber during the firing of the artillery is very complicated. After firing, the projectile is driven by the high-temperature and high-pressure gunpowder gas and starts to move from overcoming the pulling force. The projectile enters the barrel through the sloped chamber and makes a straight-line acceleration movement along the barrel axis. During the acceleration movement, the belt passes through the bore and squeezes into the rifling, and the projectile rotates along the rifle. At the same time, the burning gunpowder particles and gas also move forward with the projectile, while the gun body moves backward. There are two important physical characteristics, one is the characteristics of gas pressure changes in the chamber; the other is the movement characteristics of the projectile. These two influences and interact with each other, forming a complex firing phenomenon.

During the use of various barreled weapons, the movement of the projectile in the chamber may be blocked due to the copper hanging in the barrel, the oil coating on the inner chamber, the rifling falling off, the stripping of the belt, and the presence of foreign objects in the chamber, which may cause an accident in severe cases. This paper took a certain type of medium-caliber artillery as the research object, calculated and analyzed the change law of the pressure in the breech and the movement characteristics of the projectile when the movement in the bore of the projectile is blocked, and studied the safety problems caused by the movement of the projectile in the bore.

2. Basic parameters for calculation
The basic parameters of a certain type of medium-caliber artillery are shown in Table 1.

| Project                   | Basic parameters |
|---------------------------|------------------|
| Mass of projectile        | $m_p=6\text{kg}$ |
| Length of driving band    | $L_D=30\text{mm}$|
| Depth of rifling grooves  | $t=1.5\text{mm}$ |
Project Basic parameters

| Blocked position | $l = 2.60\text{m}$ |
| Pressure of projectile base at blocked position | $p_{dl} = 125\text{MPa}$ |
| Projectile velocity at blocked position | $v_f = 850\text{m/s}$ |

3. Research on the chamber pressure with the blocked projectile

3.1. Calculation of constant volume combustion chamber pressure when the axial space of the barrel is used as a closed space

This paper carried out the calculation of the chamber pressure of the propellant under constant volume combustion, that is, when the projectile is completely stuck, it is equivalent to the closed explosive formed when the projectile reaches the blocked position in a quasi-static state. The calculation model is that the projectile is completely stationary and the propellant burns under constant volume conditions [1]. The typical curve of its internal ballistic calculation is shown in Figure 1, and the chamber pressure results are shown in Table 2.

It can be seen from the calculation results that as the projectile position moves forward, the volume of the explosive device increases, the filling density decreases, and the maximum chamber pressure decreases. When the projectile is in the obstructed area, the calculated maximum chamber pressure of the closed explosive is 287MPa, which does not exceed the design strength of the barrel.

![Figure 1. The calculated curve of closed bomb(1.5m from the gun bore bottom).](image)

Table 2. The calculation results of closed bomb.

| Displacement of projectile from bore bottom(m) | Volume of closed bomb(dm$^3$) | Density of loading(kg·dm$^{-3}$) | Maximum pressure(MPa) |
|-----------------------------------------------|-------------------------------|----------------------------------|------------------------|
| 1.00                                         | 6.3                           | 508                              | 980                    |
| 1.50                                         | 8.6                           | 368                              | 554                    |
| 2.00                                         | 11.0                          | 288                              | 386                    |
| 2.20                                         | 12.0                          | 265                              | 344                    |
| 2.40                                         | 12.9                          | 246                              | 312                    |
| 2.60(Actual blocked position)                | 13.7                          | 231                              | 287                    |

3.2. Classical interior ballistic calculation when the projectile is completely stuck

Assuming that the projectile is completely stuck, the classic interior ballistic model (zero-dimensional model) is used for interior ballistic calculation [1]. Considering the gas work on the projectile, it is assumed that the kinetic energy of the gas after the projectile is completely converted into the heat energy of the gas when the projectile is stuck, but the pressure rising effect due to the pressure shock is not considered. The calculated typical curve is shown in Figure 2, and the calculation results are listed in Table 3.

From the calculation results, the projectile is stuck behind, the breech volume of the projectile is no
longer enlarged, and the chamber pressure will increase due to the following reasons:

1. The propellant continues to burn and rises rapidly until the burning of the propellant ends;
2. In addition, the kinetic energy of the gas in the chamber is converted into heat energy, and the temperature and pressure of the gas rise. From the calculation results, the pressure at the bottom of the chamber has risen to 231MPa, an increase of 27%, but it still does not exceed the design strength of the barrel.

![Figure 2. P-t curve when the projectile was jammed in the blocked position.](image)

| Length of projectile was jammed from bore bottom (m) | Calculation results of the projectile was jammed | Pressure of bore bottom under normal conditions(MPa) |
|-----------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 2.0                                                 | 726                                          | 314                                          | 242                                          |
| 2.2                                                 | 763                                          | 279                                          | 217                                          |
| 2.4                                                 | 795                                          | 251                                          | 197                                          |
| 2.60(blocked position)                              | 820                                          | 231                                          | 182                                          |

### 3.3. Pressure wave calculation results of stuck projectile

The lagging speed of the projectile card decreases, but the gas after the projectile still moves forward in the original state, forming an air hammer effect on the bottom of the projectile [2,3]. The one-dimensional two-phase flow model can be used to calculate the pressure rise in the chamber. The model is established to consider the conversion between the energy behind the bomb and the pressure rise effect caused by the pressure shock caused by the jam. The calculation results are as follows:

a. Calculation result of the projectile being completely stuck

The projectile stuck lagging, and the speed of the projectile tail dropped to 0. The calculation results are shown in Table 4, and the ballistic calculation curve of the stuck point of the projectile is shown in Figure 3. From the calculation results, the bottom chamber pressure at the stuck point rose sharply to 418MPa.

![Figure 3. The pressure-time curves of the bore bottom and projectile base.](image)
Table 4. The pressure value of the projectile was completely jammed.

| Maximum pressure at normal firing (MPa) | Calculation results of the projectile was jammed | Pressure of projectile base when jammed (MPa) | Pressure of bore bottom after jammed (MPa) |
|----------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|
| 330                                    | 189                                           | 418                                           |

b. Calculation result when the projectile is jammed and the velocity drops to a certain velocity value.

When the projectile is jammed, the tail velocity of the projectile drops to a certain speed value. The calculation results of the internal trajectory are shown in Table 5. The calculation curves of the projectile speed falling to 400m/s and 600m/s are shown in Figures 4 and 5.

Table 5. The maximum pressure of projectile base when the velocity of projectile drops to a certain value.

| Maximum pressure at normal firing (MPa) | Projectile velocity decreases to a certain value (m/s) | Calculation results when the projectile was jammed | Pressure of projectile base when jammed (MPa) | Pressure of bore bottom after jammed (MPa) |
|----------------------------------------|-------------------------------------------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| 100                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 200                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 300                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 400                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 330                                    | 500                                                   | 189                                           | 245                                         | 200                                         |
| 500                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 600                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 700                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 750                                    | 380                                                   | 341                                           | 302                                         | 274                                         |
| 800                                    | 380                                                   | 341                                           | 302                                         | 274                                         |

Figure 4. The pressure-time curves when the projectile velocity drops to 400m/s.

Figure 5. The pressure-time curves when the projectile velocity drops to 600m/s.

c. Calculation result analysis

From the above calculation results, it can be seen that the projectile is stuck and the speed of the projectile suddenly decreases, and the gas behind the projectile continues to move forward due to
inertia, causing the pressure behind the projectile to rise sharply, and then the pressure wave propagates to the rear of the projectile, which is reflected in the calculated value. The pressure at the bottom of the bomb rises, which in turn causes the pressure at the bottom of the chamber to rise [4]. From the calculation results, the chamber pressure has risen to a large extent, and the pressure oscillation is obvious, but the pressure wave does not diverge, and shows an overall trend of oscillation convergence.

As the movement speed of the projectile decreases, the amplitude of the bottom pressure of the projectile increases significantly. If the projectile is completely stuck, the breech pressure of the projectile will suddenly rise to a more dangerous pressure value, from 189MPa before the stuck to 418MPa. The design strength of the barrel where the pressure is close to the obstruction is twice that of the barrel, and the lumen wall of the obstructed body may undergo plastic deformation and bulge.

In addition, Table 6 shows the results of the borehole expansion verification test of the Type 59-100mm anti-aircraft gun [5]. The test adopts the method of applying grease to the inner bore to hinder the movement of the projectile and increase the bore pressure. The test carried out a comparative shooting test of the barrel with clean oil and without clean oil. During the test, the maximum pressure at the bottom of the bore \( p_m \) and the pressure at 550mm from the muzzle end face \( p_{550} \) were measured. Without removing the clean oil, a bulge occurs at 210mm from the body tube to the gun mouth when shooting the second round.

Table 6. Comparison of firing test results of 59-100mm anti-aircraft gun.

| Bore state | \( p_m \) (MPa) | \( p_{550} \) (MPa) | \( v_0 \) (m·s\(^{-1}\)) | Note          |
|------------|-----------------|---------------------|-----------------------------|---------------|
| Wipe clean | 284.8           | 108.8               | 902.4                       | 3rds, on average |
| Greased    | 284.4           | 231.6               | 870.1                       | 1rds          |
| Greased    | 285.8           | 240.8               | 860.1                       | 1rds          |

The test concluded that due to the high viscosity of the gun oil, the movement of the projectile was hindered, and the pressure peak formed at the bottom of the projectile exceeded the design strength of the barrel, which caused plastic deformation of the barrel wall and bulging. This conclusion is consistent with the calculation of the pressure of the projectile after the lagging movement of the projectile in this paper.

4. Analysis of the characteristics of blocked movement of the projectile

4.1. Basic assumptions
a. Assuming that the projectile is blocked by a foreign body when it moves in the barrel;
b. The material of the foreign body is copper, as shown in Figure 6, the external dimension of the foreign body is 5mm× 4mm× 2.5mm (length× width× height);
c. The projectile is a rigid body, and the deformation of the projectile is not considered;
d. The projectile collides with a foreign body, the foreign body deforms and moves with the projectile, and the speed of the projectile remains unchanged.

Figure 6. Schematic of the projectile was blocked by a foreign body.

4.2. Calculation of projectile movement
Assuming that the projectile collides with a foreign body, the maximum force of the projectile is the
condition that the foreign body produces plastic deformation. At this time, the resistance of the projectile after being blocked by the foreign body:

\[ f = \mu \sigma_b S \sin \alpha + \sigma_b S \cos \alpha \]  

(1)

In the formula, \( \mu \) is the friction coefficient, which is 0.2; \( \sigma_b \) is the yield limit of the copper foreign body before the projectile, which is 300MPa; \( \alpha \) is the angle between the surface of the projectile and the foreign body and the axial direction of the barrel; \( S \) is the contact area between the foreign body and the projectile.

The thrust of the projectile by the bottom pressure of the projectile is:

\[ P = p_d S_d \]  

(2)

In the formula, \( p_d \) bomb bottom pressure, \( S_d \) is the force area of bomb bottom.

Then the projectile acceleration is:

\[ a = \frac{P \cdot f}{m} \]  

(3)

As shown in Figure 6, the angle between the surface of the projectile and the tangent surface of the foreign body and the axial direction of the barrel is \( \alpha \approx 7^\circ \) through the drawing method.

Table 7. Calculation results of projectile motion after being blocked.

| Material | \( \alpha \) | \( S \) | \( a \) | Overload |
|----------|----------|--------|--------|---------|
| Cuprum   | 7°       | 20.16mm² | 99134m/s² | 10116g  |

4.3. Analysis of the influence of foreign bodies on the projectile and the part of the barrel

Assuming the projectile is a rigid body, without considering the deformation of the projectile, according to the law of conservation of momentum, the impulse received by the projectile is:

\[ F = m \cdot v / \Delta t \]  

(4)

Where \( m \) is the mass of the foreign matter before the projectile, \( v \) is the velocity of the projectile, \( \Delta t \) is the time between the foreign matter and the projectile, \( f \) is the force that the projectile receives after being blocked by the foreign matter, and its direction is the direction of the speed change, which is the direction of the bore axis.

The pressure on the part of the projectile surface in contact with the foreign body is:

\[ p = F \sin \alpha / S \]  

(5)

Where \( S \) is the contact area, and the pressure on the corresponding body tube is:

\[ p_{sh} = p \sin \alpha \cos \alpha \]  

(6)

The elongation of copper is 60%, so the maximum deformation of the copper foreign body here is 2.5mm \( \times \) 60\% = 1.5mm. From this, the collision time that produces this maximum deformation can be calculated as:

\[ \Delta t = (1.5 / \sin \alpha) / v_f \approx 0.015 \text{ms} \]

The density of copper is 8.93g/cm³, which can be obtained by formulas (4), (5) and (6):

\[ F \approx 25 \text{kN}, \]

\[ p = 151 \text{MPa}, \]

\[ p_{sh} \approx 150 \text{MPa} \]

4.4. Results analysis

From the above calculation, if the deformation of the projectile and the foreign body is not considered, the condition of the plastic deformation of the foreign body is the maximum force condition of the projectile. The foreign body before the projectile has a very small influence on the projectile overload, and the projectile movement still maintains the positive overload.

After the projectile collides with the foreign body, when the two moves together at the speed of the projectile, after calculation, the local impulse of the projectile after being blocked by the foreign body is 25kN. Since the angle between the direction of the impulse and the cone of the projectile is very
small, the projectile is only subject to pressure. It is 151MPa, and the action time is only 0.015ms. It has little work on the projectile, and the projectile is less affected and damaged.

During a collision, the pressure on the body tube is 150MPa. Under this impact, the pressure on the body tube does not exceed its design strength.

During the movement of the projectile in the bore, if the reverse acceleration of the projectile is obstructed to reach or exceed the fuse safety threshold $a_0$, the projectile will explode prematurely in the bore. According to the above calculation, the overload of the projectile during the blocked movement is about 10116 g, which does not exceed the safety threshold of the fuse. Under the above basic assumptions, it will not cause premature explosion in the chamber.

However, it is worth noting that if the movement of the projectile in the bore is severely stuck, even causing its movement speed to drop rapidly, it is likely that the reverse acceleration of the projectile will exceed the fuse safety threshold $a_0$, which will cause the projectile to explode prematurely in the bore.

5. Conclusion
From the above calculation and analysis, the following conclusions can be drawn:

1) The movement of the projectile in the chamber is blocked, which will cause the chamber pressure to rise to a certain extent. When the obstruction is severe, the increased pressure can cause plastic deformation (expansion) of the lumen wall of the body.

2) Excessive objects such as copper hanging in the inner chamber and the bullet belt falling off can cause the movement of the projectile in the chamber to be blocked. However, such foreign objects in front of the copper projectile have little effect on the projectile overload, and will not cause shooting safety problems under normal circumstances.

The above analysis and calculations are all carried out under certain basic assumptions. The calculation results have certain limitations. For example, in the motion calculation, the deformation of the projectile and the barrel is not considered. However, the calculation results give a certain degree of the change trend of the breech pressure, the force on the barrel and the movement of the projectile after the movement of the projectile is blocked. The calculation results can provide a reference for the barrel design or troubleshooting. In the design of artillery and projectiles, full attention should be paid to the design of projectile compatibility, and the influence of factors such as the barrel structure, processing deviation, belt structure, and projectile strength on the internal ballistic performance and shooting safety should be considered.

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