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# Research on the Influence of Some Factors on the Departure Angle of Warheads When Firing a Series

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**ABSTRACT:** In this article, the equation for determining the projectile's departure angle taking into account the effects of several shot parameters is established. The parameters of the shot include the speed of rotation around the axis of the rotating part when fired; and the curvature of the barrel due to the temperature of the shot. Numerical calculations are applied to 37mm anti-aircraft guns. Research results show that: The speed of rotation around the axis of the rotating part when firing has a significant effect on all types of artillery, especially on long-barreled artillery; While the shot temperature significantly affects the departure angle of the warhead when firing in series. This influence causes errors in the firing. The departure angle becomes larger as the rotation speed becomes faster; The departure angle of the bullet when firing the 5th, 10th, and 15th bullets is 0.0117, 0.015, 0.0175, 0.0185, 0.0199, and 0.0206 rad, respectively, when taking into account the shot temperature. This result is used as data to provide effective barrel design solutions and barrel cooling methods.

**KEYWORDS:** Rotating part; Shot temperature; departure angle; interior ballistic; barrel design.

## I. INTRODUCTION

In guns, increasing the energy of the shot and the initial velocity of the bullet leads to increased heating of the barrel wall. On the other hand, when a shot occurs, the barrel not only deforms but also oscillates, greatly affecting the power, shooting accuracy, and durability of the weapon. Shooting accuracy is not only influenced by subjective factors adjusted by humans but also by factors generated by the shot itself. There are many factors created by the shot that reduce shooting accuracy such as the static curvature of the barrel; rotation around the axis when fired; barrel warping due to shot temperature; and manufacturing error. To evaluate the influence of the above factors on shooting accuracy, the quantity of the bullet's departure angle is used.

The angle of departure is created by the velocity vector of the warhead and the initial position of the tangent line to the actual barrel axis at the muzzle part of the cannon at the moment before firing. The departure angle is divided into 2 main components: Vertical departure angle, and horizontal departure angle. The vertical departure angle and the horizontal departure angle are understood as projections of the departure angle in the respective plane onto the vertical and horizontal planes.

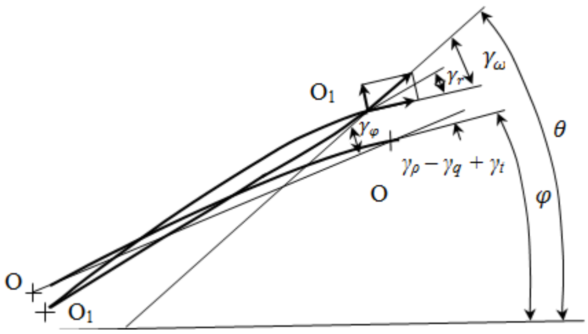


**Fig. 1. Model for determining the departure angle**

The actual vertical departure angle is the geometric sum of the projections on the vertical plane of the six angles in space:

$$\gamma = \theta - \varphi = \pm\gamma_\varsigma - \gamma_q + \gamma_\varphi - \gamma_\eta + \gamma_\omega \pm \gamma_T \qquad (1)$$

Where:

$\theta$ - lift angle;

$\varphi$ - range angle;

$\gamma_\varsigma$ - The angle at the mouth of the barrel occurs due to the curvature of the barrel; The angle at the barrel mouth $\gamma_\varsigma$ appears due to errors during the barrel manufacturing process. This angle is unstable and depends on the level of perfection of heat and mechanical processing technology for the barrel, barrel length, and other factors.

$\gamma_q$ - Angle created by the curvature of the barrel mouth due to gravity; The departure angle components $\gamma_\varsigma$ and $\gamma_q$ are constant for a barrel. The influence of these angles on the precision of the shot can be well overcome by adjusting the aiming.

$\gamma_\eta$ - The angle created when the barrel of the cannon is treated as an elastic body;

$\gamma_\omega$ - The angle between the long velocity vector of the warhead and the composition vector of the long velocity vector with the horizontal velocity vector of the warhead at the moment the warhead exits the barrel;

$\gamma_T$ - The angle is created due to uneven heating in the barrel wall when the wall thickness is different.

$\gamma_\varphi$ - The angle created by the barrel's rotation around the pivot of the rotating part, which is measured as the angle between the tangent at the muzzle point in the stationary position before firing and at the time of firing;

In the world, there have been many studies on the factors affecting the projectile's departure angle such as the influence of the semi-link phase [3], and the influence of the bullet structure [4-6], some studies have proposed the law of barrel wall temperature and its influence on the projectile's departure angle [7-10]. In general, previous studies mainly focused on the influence of the shot on the oscillation of the barrel, but no research has mentioned the swing of the range mechanism on the angle of departure of the projectile. In the framework of this article, the author has studied, built a model, and established the equation to determine the departure angle of the 37mm anti-aircraft artillery bullet, taking into account the rotation speed of the rotating part during firing. In addition, the influence of barrel temperature changes during firing is also mentioned in this study.

## II. SET UP THE CALCULATION MODEL

### *A. Determine the departure angle considering the rotation speed of the rotating part*

Under the effect of external force, the rotating part will rotate around the axis while the bullet moves in the barrel $\gamma_\varphi$.

To calculate $\gamma_\varphi$, some assumptions are used as follows:

- The rotating part (including the barrel, the recoil brake device, and the gun trough) is a rigid system with a constant radius of curvature ρ.

- The axis of rotation at the moment of projectile departure is not moved.

- The barrel and rotating part rotates around the axis.

- The moment of the balancing mechanism is greater than the mass moment (unbalanced moment $\Delta M > 0$).

To find the angle $\gamma_\varphi$, let's build an equation to describe the rotation of the rotating part around the trough ear axis when the bullet is still moving in the barrel.

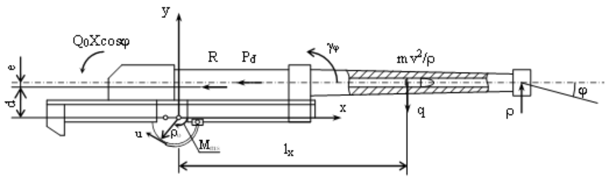


**Fig. 2. Diagram of forces acting on the range block when firing**

With the above assumptions, after the time of movement of the warhead in the barrel, the equation can be written based on the mechanical theory of angular momentum of the system motion:

$$\frac{dG_{кр}}{dt} = \sum M_{F0} \qquad (2)$$

The angular momentum of the up and down mass movement of the cannon relative to the axis $G_{к.о}$ is equal to:

$$G_{к.о} = G_{л.о} + G_{о.о} + G_{с.о} \qquad (3)$$

where

$G_{л.о}$ - angular momentum of the cannon trough.

$$G_{л.о} = B_{л.о}\dot{\gamma}_\varphi \qquad (4)$$

$B_{л.о}$ - moment of inertia of the cannon chute relative to the rotating axis;

$G_{о.о}$ - angular momentum of the recoil part:

$$G_{о.о} = \sum(\mu V_y x + \mu V_z y)$$

$G_{с.о}$ - angular momentum of the warhead;

$\mu$ - mass element.

After transformation, the angular momentum expression of the receding block is written in the following form:

$$G_{о.о} = \dot{\gamma}_\varphi \sum \mu(x^2 + y^2) + M_o V d \qquad (5)$$

where

$M_0$ - mass of the recoiling part;

$V$ - moving speed of the recoil part.

Angular moment of the warhead:

$$G_{с.о} = -\dot{\gamma}_\varphi \sum \mu_с (x_с^2 + y_с^2) - mv(d+e). \qquad (6)$$

Substituting the expressions of angular momentum $G_{л.о}$, $G_{о.о}$, and $G_{с.о}$ into equation (3), we get:

$$G_{к.о} = B_{л.о}\dot{\gamma}_\varphi + \dot{\gamma}_\varphi \sum \mu(x^2+y^2) + M_0 V d + \dot{\gamma}_\varphi \sum \mu_с (x_с^2 + y_с^2) - mv(d+e). \qquad (7)$$

The derivative of angular momentum versus time, the following expression changes as follows:

$$\frac{dG_{к.о}}{dt} = B_{к.о}\ddot{\gamma}_\varphi + 2\dot{\gamma}_\varphi (M_0 V \xi - mvx) + M_0 d \frac{dV}{dt} m(d+e)\frac{dv}{dt}$$

(8)

where

$B_{к.о}$ - moment of inertia of the cannon trough part to the shaft axis;

$\xi$- recoil distance;

$x$ - The distance the bullet moves through the barrel.

Equation of motion of the warhead:

$$m\frac{dv}{dt} = P_{сн} - F \qquad (9)$$

Equation of motion of the recoil part:

$$M_0 \frac{dV}{dt} = P_{кн} - R \qquad (10)$$

Therefore, when $P_{сн} = P_{кн}$, expression (10) is rewritten as follows:

$$\frac{dG_{к.о}}{dt} = B_{к.о}\ddot{\gamma}_\varphi + 2\dot{\gamma}_\varphi (M_0 V \xi - mvx) - P_{кн} e - Rd \qquad (11)$$

The sum of the force moments acting on the cannon trough:

$$\sum M_{F_0} = \Delta M + Q_0 x\cos\varphi - u\varsigma_0 - ql_x + \frac{mv_x^2}{\varsigma} l_x - M_T \quad (12)$$

where

$Q_0$ - weight of the recoil part;

$u$ - reaction force of the dental arch of the range structure;

$\varsigma_0$ - preliminary circular radius of the tooth arch of the reach mechanism;

$l_x$ - the lever arm of the warhead's gravity relative to the axial axis;

$M_T$ - moment of friction in the shaft, whose value is proportional to the angular velocity of rotation of the gun chute:

$$M_T = k\dot{\gamma}_\varphi \quad (13)$$

$k$ - proportionality factor.

The reaction moment of the gear tooth of the range mechanism can be calculated as the product of the angular stiffness of the range mechanism and the rotation angle:

$$u\varsigma_0 = c\gamma_\varphi \quad (14)$$

Substituting the above two expressions into equation (12), we get:

$$\sum M_{F_0} = \Delta M + Q_0 x\cos\varphi - c\gamma_\varphi - ql_x + \frac{mv_x^2}{\varsigma} l_x - k\dot{\gamma}_\varphi \quad (15)$$

Substituting into equation (11) expressions $\frac{dG_{\text{к.о}}}{dt}$, $\sum M_{F_0}$, we get:

$$B_{\text{к.о}}\ddot{\gamma}_\varphi + [2(M_0 V\xi - mvx) + k]\dot{\gamma}_\varphi + c\gamma_\varphi =$$
$$= P_{\text{кн}} e + Rd + \Delta M + Q_0 x\cos\varphi + \frac{mv_x^2}{\varsigma} l_x - ql_x \quad (16)$$

In actual calculations, when determining the angle of rotation of the block up and down at time t, with not a large error, the Coriolis forces of the receding block and the warhead can be considered equal. Then equation (16) can be rewritten as follows:

$$\ddot{\gamma}_\varphi + 2\lambda\dot{\gamma}_\varphi + \omega^2\gamma_\varphi = \frac{\sum M(t)}{B_{\text{к.о}}} \quad (17)$$

where

$\lambda$ - damping coefficient of transverse vibrations, determined experimentally. For current artillery pieces, this value varies between 2.5 and 4.0;

$\omega = \sqrt{\frac{c}{B_{\text{к.о}}}}$ - The horizontal natural oscillation frequency of the part goes up and down;

$\sum M(t) = P_{\text{кн}} e + Rd + \Delta M + Q_0 x\cos\varphi + \frac{mv_x^2}{\varsigma} l_x - ql_x$ - the current value of the total moment. If the value of the equatorial moment of inertia of the up and down block is considered constant over the time variation Δt, the rotation angle of the rotating part is determined as follows [11-15]:

$$\gamma_\varphi = \left(\gamma_{\varphi_0}\cos pt + \frac{\dot{\gamma}_{\varphi_0} + \lambda\gamma_{\varphi_0}}{p}\sin pt\right)e^{-\lambda t} + \frac{M_{(0)}}{B_{\text{к.о}}\omega^2}\left[1 - e^{-\lambda t}\left(\frac{\lambda}{p}\sin pt + \cos pt\right)\right] + \frac{b}{B_{\text{к.о}}\omega^2}\left[t - \frac{e^{-\lambda t}}{\omega^2}\left(\frac{p^2-\lambda^2}{p^2}\sin pt - 2\lambda\cos pt\right) - \frac{2\lambda}{\omega^2}\right], \quad (18)$$

where

$p$ - The frequency of the horizontal natural vibrations of the up and down block takes into account the damping of the vibrations:

$p = \sqrt{\omega^2 - \lambda^2}$;

$\gamma_{\varphi_0}$ - The initial rotation angle of the rotated part takes into account the previously considered segments;

$\dot{\gamma}_{\varphi_0}$ - the initial rotational speed of the rotating part at the time being considered.

***B. Determine the departure angle considering the shot temperature***

To establish the equation for the departure angle, several assumptions are used as follows:

- Let the values of the angles $\gamma_\varsigma$, $\gamma_q$, $\gamma_\eta$, $\gamma_\varphi$, $\gamma_\omega$ be zero;
- The barrel wall is considered irregular in thickness;
- The horizontal departure angle is considered to be zero.

Due to the uneven thickness of the barrel wall, the thin wall of the barrel cross section will be heated to a higher temperature than the thick barrel wall when fired. This is what causes the different elongations along the barrel axis. This elongation causes the barrel to bend and form a departure angle $\gamma_T$.

The model for determining the departure angle is shown in Figure 3.

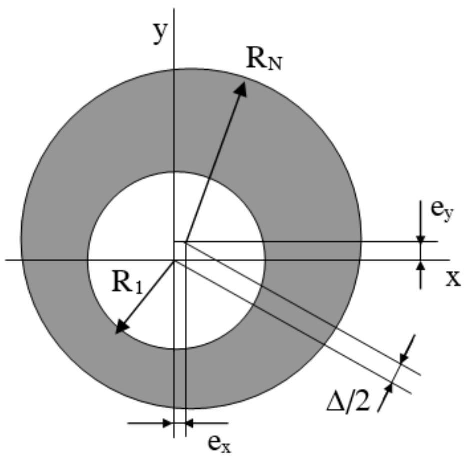


**Fig. 3. Model for determining the departure angle when the barrel wall thickness is different**

The relative elongation strain for a point of the barrel with coordinates $\theta$ and $r$ with free expansion can be found by the formula:

$$\varepsilon_z^0 = \alpha \Delta T(\theta, r) - \frac{\sigma_z^0}{E} \quad (19)$$

Where: $\alpha$ - elongation coefficient; $\Delta T$ - surface temperature difference; $\sigma_z^0$ - The elongation stress at the point is determined by the coordinates $\theta$ and $r$.

When $\varepsilon_z^0 = 0$ the elongation stress is determined:

$$\sigma_z^0 = \alpha \Delta T(\theta, r) E \quad (20)$$

Bending moment in each barrel cross-section:

$$M_и^0 = \int_{R_1}^{R_N} \int_0^{2\pi} \sigma_z^0 . r^2 . \sin\theta . dr . d\theta \quad (21)$$

Or $$M_и^0 = \int_s \sigma_z^0 r \cos\theta ds$$

With $ds = d\theta dr$, Equation (21) can be rewritten as:

$$M_и^0 = \int_s \alpha \Delta T(\theta, r) E r \cos\theta d\theta dr \quad (22)$$

The cross-sectional temperature distribution of barrel walls of different thicknesses is determined by the following formula:

$$\Delta T(\theta, r) = \frac{\Delta T_1 (1 + \cos\theta)}{2} + \frac{r - r_1}{r_2 - r_1} \frac{1 + \cos\theta}{2} (\Delta T_2 - \Delta T_1) \quad (23)$$

Where:

$\Delta T_1$ - The maximum heat reduction on the inner surface of the barrel;

$\Delta T_2$ - The maximum heat reduction on the outer surface of the barrel.

Substituting the value (23) into equation (22), the result obtained when integrating equation (22) is as follows:

$$M_и^0 = \alpha E (\Delta T_2 - \Delta T_1) \frac{\pi}{8} \left\{ 2 \left[ \frac{\Delta T_1}{\Delta T_2 - \Delta T_1} - \frac{r_1}{r_2 - r_1} \right] \left( r_2^3 - r_1^3 \right) + \frac{r_2^4 - r_1^4}{r_2 - r_1} \right\} \quad (24)$$

The bending moment can be determined by the following formula:

$$M_и^0 = \frac{EI}{\varsigma} \quad (25)$$

Where: $\varsigma$ - the radius of curvature of the barrel is considered.

Balancing the right side of equations (24) and (25), Value $\varsigma$ is determined:

$$\varsigma = \frac{b(r_2 - r_1)}{\alpha(\Delta T_2 - \Delta T_1) \left\{ 3 + 4 \frac{r_2^3 - r_1^3}{r_2^4 - r_1^4} \left[ \frac{\Delta T_1}{\Delta T_2 - \Delta T_1} (r_2 - r_1) - r_1 \right] \right\}} \quad (26)$$

Angle $\gamma_т$ is determined in $\varsigma$ terms of as follows:

$$\gamma_т = \frac{1000.l}{\varsigma} \quad (27)$$

The final expression for determining the departure angle $\gamma_т$ has the following form [16-18]:

$$\gamma_т = \frac{\alpha l (\Delta T_2 - \Delta T_1) 10^2}{2(r_2 - r_1)} \left\{ 1 + \frac{4}{3} \frac{r_2^3 - r_1^3}{r_2^4 - r_1^4} \left[ \frac{\Delta T_1}{\Delta T_2 - \Delta T_1} (r_2 - r_1) - r_1 \right] \right\} \quad (28)$$

## III. RESULTS AND DISCUSSION

### A. *Input parameters*

The 37mm anti-aircraft gun is an automatic cannon, firing in tandem, with a rate of fire that can reach 160 to 180 rounds per minute. Therefore, the temperature and the rotating speed of the angle when the bullet leaves the barrel are different after each shot. This change is what causes the deviation of the departure angle when firing. Equation (18) shows that: the departure angle when considering the rotation of the range angle is mainly affected by the angular speed of the range rotation angle ω. To evaluate this influence, the angle of rotation speed is changed to determine the law of the barrel's departure angle. The input parameters to determine the departure angle when calculating the rotation angle of the range are presented in Table 1:

**Tab. 1. Input parameters [19-20]**

| Parameters | *Symbol* | Unit | Value |
|---|---|---|---|
| Mass of the recoil part | $Q_0$ | kg | 130 |
| Mass of the warhead | $q$ | kg | 0.196 |
| Mass of propellant | $\omega$ | kg | 0.077 |
| Moment of inertia of the rotating part | $B_к$ | N.m.s$^2$ | 79.5 |
| Moment of inertia of the rotating part relative to the trough axis | $B_{к.о}$ | N.m.s$^2$ | 151.5 |
| The distance from the center of mass up and down to the cannon's trough ear axis | $d_0$ | m | 0.8 |
| Distance from barrel mouth to trough ear axis | $l_s$ | m | 2.315 |
| Initial recoil braking force | $R_0$ | N | 4100 |
| The recoil braking force is at the moment the warhead flies out of the barrel | $R_d$ | m/s | 16000 |
| Muzzle velocity of the bullet | $v_d$ | m/s | 870 |
| Distance traveled by the warhead inside the barrel | $l_d$ | m | 1.875 |
| Warhead movement time | $t_d$ | s | 0.035 |

The results of solving the equation to determine the departure angle of a 23mm anti-aircraft gun when firing a series of 3 bullets are shown in Figure 4:

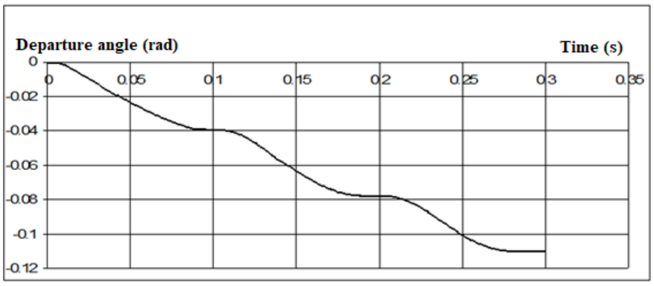


**Fig. 4. Graph of departure angle over time**

***B. Investigate the effect of rotation speed on the gun's departure angle***

To evaluate the influence of the change in angular speed on the gun's departure angle, The angular speed of the rotating part ω is taken as 0.5 rad, 1.0 rad, and 1.5 rad respectively. Calculation results are shown in Figure 5 and Table 2.

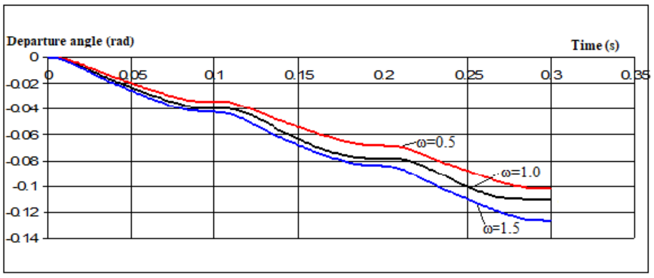


**Fig. 5. Calculation results of the departure angle over time**

**Tab. 2. Results of calculating the angle of flight according to the number of shots**

| Number of shot | ω (Rad/s) | $\gamma_\varphi$ (Rad) |
|---|---|---|
| 1 | 0.62 | 0.041 |
| 2 | 0.75 | 0.085 |
| 3 | 1.02 | 0.125 |
| 4 | 1.34 | 0.215 |
| 5 | 1.12 | 0.159 |
| 6 | 0.89 | 0.106 |

*Comment:*

Figure 5 and table 2 show that:

- As the rotation speed of the range angle increases, the projectile's departure angle also increases. The shape of the graph in Figure 5 shows the significant influence of rotation speed on the projectile's departure angle.

- In addition, the ejection angle also changes according to the number of consecutive shots. When firing 6 consecutive shots, the ejection angle reaches its maximum value at the time the 4th shot exits the barrel.

***C. Investigate the effect of shot temperature on the projectile's departure angle***

To investigate the effect of shot temperature on the deviation of the departure angle, the value of the departure angle is determined according to the number of shots respectively 5, 10, 15, 20, 25, and 30 shots. Calculation results are shown in Table 3.

**Tab. 2. Calculation results of the departure angle according to the number of shots**

| Number of shot | $\Delta T_1$ (°C) | $\Delta T_2$ (°C) | $\varsigma$ (m) | $\gamma_T$ (Rad) |
|---|---|---|---|---|
| 5 | 300 | 250 | 250.97 | 0.0117 |
| 10 | 370 | 330 | 160.38 | 0.0150 |
| 15 | 420 | 390 | 137.86 | 0.0175 |
| 20 | 460 | 420 | 127.18 | 0.0185 |
| 25 | 490 | 440 | 120.61 | 0.0199 |
| 30 | 510 | 450 | 117.11 | 0.0206 |

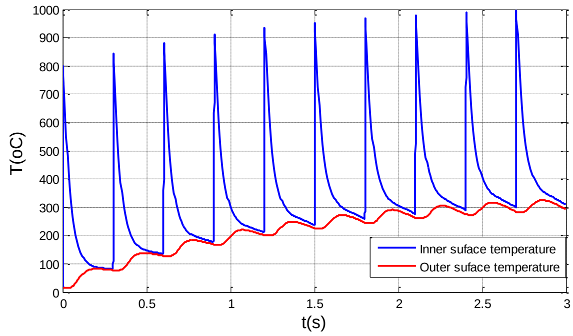


**Fig. 6. Temperature graph of inner and outer walls of the artillery**

Comment:

The results of calculating the difference between the outer surface temperature $\Delta T_2$ and the inner surface temperature $\Delta T_1$ are shown in Table 3. The temperature in the thick part ($R_N$ - $R_1$ + $\Delta/2$) of the barrel wall during firing is always lower than the temperature in the thin part ($R_N$ - $R_1$ - $\Delta/2$). During the firing time, the temperature difference between $\Delta T_1$ and $\Delta T_2$ increases rapidly.

The departure angle of the sections along the barrel length when firing series 5, 10, 15, 20, 25, and 30 is shown in Figure 6. The figure also shows that the thin wall of the barrel will be heated faster after each shot, so the elongation will be greater than the thick wall. This temperature difference is larger the larger the number of shots. Therefore, the error of the automatic cannon's departure angle is greatly affected by the firing temperature.

## CONCLUSIONS

In this article, the equation to determine the projectile's departure angle when taking into account several impact factors of the shot is established. The impact factors of the shot are mentioned as the rotation speed of the retreating block when fired and the temperature of the shot. With the survey results obtained, some conclusions are drawn as follows:

- The rotation speed of the range block occurs for all guns when fired. The reason is the hill of the long-range base;
- The difference in barrel wall temperature when the thickness of the barrel wall is different is the cause of the deviation of the departure angle when firing in series;
- For long-barreled cannons, the temperature of the shot has a greater effect on the angle of departure, so the error of the angle of fire is greater;
- Accurate determination of the cannon's departure angle is the basis for accurately determining the cannon's firing angle;
- Research results show that the deviation of the barrel wall thickness is the main cause of the departure angle deviation when firing series. Therefore, machining accuracy needs to be maximized when making cannon barrels.

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