Numerical Calculation and Analysis of Gun Barrel Heat Transfer

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Abstract. With the help of classical interior ballistic model, the thermal environment parameters inside and outside the gun barrel are analyzed and calculated. Then, the finite difference method is used to calculate the heat transfer process of the barrel, and the distribution of the peak temperature and radial temperature field is obtained. The results show that the inner wall temperature increases rapidly at first, and the speed of temperature increase gradually decreases when the inner wall temperature reaches the extreme value, and the speed of temperature decrease gradually. In the case of continuous firing, the temperature does not necessarily decrease monotonically in the radial coordinates of the barrel. Under certain circumstances, one or more extreme points may appear.

1. Introduction

At present, the research on the determination method of gun barrel life state is still in the static test stage, and these detection methods are difficult to be applied in the actual combat and training process of the army. The lumped parameter method applied by Lawton and Laird [1] can calculate the heat transferred from the propellant gas to the barrel wall, and then estimate the wear amount of the inner wall of the barrel. Conroy [2] applied the one-dimensional two-phase flow interior ballistic model, simplified the turbulent boundary layer, and solved the heat transfer coefficient of the boundary layer by using the flat plate model, so as to calculate the wall temperature according to the one-dimensional heat conduction equation. Chen Longsen [3] and others calculated the peak temperature and temperature field distribution of the inner wall of the barrel when the gun barrel was fired with the aid of the unstable quasi one-dimensional flow interior ballistic model, and estimated the single heat erosion based on the calculated peak temperature of the inner wall. Samuel [4,5] and others put forward the thermochemical ablation model of barrel life loss, which includes thermochemical model, interior ballistic calculation, boundary layer calculation, barrel ablation calculation and barrel mechanical wear analysis based on ABAQUS. Wu Bin [6] and others have deeply studied the ablation mechanism of barrel bore, and established the theoretical calculation formula for the thickness of thermal ablation layer of barrel based on the assumption of semi-infinite object and the second boundary condition assumption of heat transfer. This paper mainly studies the heat transfer characteristics of single shot and continuous fire.
2. Heat transfer analysis of barrel

When the gun is firing, the heat transfer environment inside the gun chamber changes more complex, which can be divided into the following three periods: in bore motion period, aftereffect period and interval period.

2.1. In bore motion period

According to the interior ballistic equations, the interior ballistic calculation program is compiled by MATLAB, and the interior ballistic numerical calculation is carried out. The charge design of a certain type of gun is shown in Table 1, because the charging mode of a certain type of gun is divided into 0~6 kinds of charges.

Table 1. Charge design of a certain gun

| Charge number / # | 0    | 1    | 2    | 3    | 4    | 5    | 6    |
|-------------------|------|------|------|------|------|------|------|
| Charge quality / kg | 8.185| 7.295| 4.14 | 3.01 | 2.445| 1.88 | 1.315|
| Initial velocity / (m/s) | 655  | 606  | 511  | 421±4| 380±4| 335±3| 282  |

The above data in Table 1 are substituted into the internal ballistic calculation program to complete the internal ballistic calculation. After calculation and processing, the variation law of pressure and velocity in a certain type of gun is shown in Figure 1.

Figure 1 shows the variation law of average pressure in bore and velocity of projectile with time under the condition of No.0 and No.3 charge during the motion period in bore of a certain type of gun. The following conclusions can be drawn from the calculation results of MATLAB in bore motion period program. (1) The in-bore motion period of No.0 charge is about 10.5ms, and that of No. 3 charge is about 14ms. As shown in Figure 1 (a), the in-bore motion period of No. 0 charge is earlier than that of No. 3 charge. (2) The results show that the maximum pressure in bore is 250.98mpa, the final velocity of projectile is 659.60m/s, the maximum pressure is 150.33mpa and the final velocity is 426.35m/s. This shows that the calculation results of the motion period in bore are basically reliable. (3) The pressure in gun chamber rises rapidly, reaches the maximum value and then decreases rapidly. The overall change rate of bore pressure is positively related to the charge weight.

2.2. Aftereffect period

According to the isentropic relation and momentum theorem, the theoretical calculation formula of the characteristic parameters of propellant gas in the aftereffect period can be deduced.
\[ \begin{align*}
    p &= p_1 (1 + Bt)^{\frac{2k}{k-1}} \\
    T &= T_0 (1 + Bt)^{\frac{2}{k-1}} \\
    \rho &= \rho_0 (1 + Bt)^{\frac{2}{k-1}} \\
    v_g &= \sqrt{kp / \rho}
\end{align*} \tag{1} \]

Where: \( p \) is the muzzle pressure of propellant gas at time \( t \), \( T \) is the temperature of gunpowder gas at time \( t \), \( \rho \) is the density of gunpowder gas at time \( t \), \( v_g \) is the muzzle flow velocity of gunpowder gas at time \( t \); \( p_1, T_0, \rho_0 \) are muzzle pressure, gas temperature in bore and gas density in bore at the beginning of aftereffect period, \( k \) is adiabatic index, \( B \) is the action coefficient of gunpowder gas in aftereffect period.

2.3. Interval period

In the interval period, the inner and outer walls of gun barrel are in the state of natural convection heat transfer with the outside air. Since the outer wall of the barrel is always exposed to the air, it can be considered that the convective heat transfer coefficient between the two remains unchanged. According to experience, the convective heat transfer coefficient \( h_0 \) between the outer wall and the air can be taken as 50W / (M² · K). In the interval period, the natural convection heat transfer coefficient between the inner wall of the barrel and the gas in the bore is approximately the same as that of the outer wall, which is 50W / (M² · K), and the gas temperature in the bore is the ambient temperature.

3. Establishment of heat transfer model for barrel

3.1. Governing equation of heat conduction

In fact, the heat conduction problem in the process of gun firing is a three-dimensional unsteady heat conduction problem. The differential equation of three-dimensional unsteady heat conduction is described as follows

\[ \frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{2} \]

Where \( a \) is thermal diffusivity, also known as the thermal conductivity. The definition of \( a \) is

\[ a = \frac{\lambda_s}{\rho_s c_s} \tag{3} \]

Where: \( \lambda_s \) is thermal conductivity, \( \rho_s \) is material density, \( c_s \) is specific heat capacity.

In order to simplify the analysis and calculation, the heat conduction problem in the process of gun firing is simplified to one-dimensional unsteady heat conduction problem, and then the heat conduction differential equation is

\[ \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{4} \]

Where, \( T_b \) is the barrel temperature.
3.2. Boundary conditions for convective heat transfer

The convective heat transfer process occurs on the inner and outer walls of the barrel, so the boundary problems should be discussed separately. Heat transfer equation of inner boundary

\[ \lambda \frac{\partial T}{\partial x} \bigg|_{r=R} + h_s(T_s - T) \bigg|_{r=R} = 0 \]  

(5)

The heat transfer equation of the outer boundary is

\[ \lambda \frac{\partial T}{\partial x} \bigg|_{r=r} + h_R(T_r - T_R) \bigg|_{r=r} = 0 \]  

(6)

Where \( h_s \) is the heat transfer coefficient at the inner boundary, \( h_R \) is the heat transfer coefficient at the outer boundary, \( T_r \) is the gas temperature in the bore, and \( T_R \) is the gas temperature at the outer boundary.

3.3. Finite difference equation of barrel heat conduction

In this study, the inner and outer boundaries of barrel heat transfer have regular geometry. Therefore, the finite difference method is used to establish the mathematical model of barrel heat transfer. Figure 2 is the discrete schematic diagram of one-dimensional heat transfer of barrel. As shown in the figure, the gun barrel is divided into \( n \) layers from the inner diameter \( r \) to the outer diameter \( R \), and the thickness of each layer is \( \delta \), and the number of each layer is \( 1, 2, 3 \cdots i \cdots n \), the time is discretized, and the length of each period is \( \tau \), and the number of each period is \( 0, 1, 2 \cdots j \cdots \). The origin of the \( x \)-axis is set at the beginning \( r \) of the inner diameter, so there is

\[
\begin{align*}
    x_i &= i\delta \\
    \delta &= \frac{R-r}{n} \\
    t_j &= j\tau \\
    (i = 1,2, \ldots, n) \\
    (j = 0,1, \ldots)
\end{align*}
\]  

(7)

Figure 2. One dimensional heat transfer discrete diagram of barrel

For \( T(x_r, t_j) \), i.e. node \( i \), the temperature at the \( j \)-th moment can be expressed as \( T_i^j \), where the superscript represents the time position and the subscript space position. The central difference formula of the second derivative of temperature \( T_i^j \) of node \( i \) at time \( j\tau \) to coordinate \( x \) is

\[
\frac{\delta^2 T_i}{\delta x^2} \approx \frac{1}{\delta^2}(T_{i+1}^j + T_{i-1}^j - 2T_i^j)
\]  

(8)

The forward difference formula of the first order partial derivative of \( T_i^j \) for time \( t \) is
\[
\frac{\partial T_i}{\partial t} = \frac{1}{\tau} (T_{i+1}^{j+1} - T_i^j)
\]  

(9)

Substituting equations (8) and (9) into equation (4) can be obtained

\[
T_i^{j+1} = \frac{a\tau}{\delta^2} (T_{i+1}^j + T_{i-1}^j) + (1 - \frac{2a\tau}{\delta^2})T_i^j
\]  

(10)

Equation (10) is a one-dimensional difference equation for unsteady heat conduction.

The first derivative of temperature \( T_i^{j+1} \) to coordinate \( x \) in equation (5) is forward difference, the first derivative of temperature \( T_i^j \) to coordinate \( x \) in equation (6) is backward difference, the difference equation of inner boundary and outer boundary temperature calculation is obtained by combining formula (10), as shown in equation (11)

\[
\begin{align*}
T_i^{j+1} &= \frac{2a\tau}{\delta^2} (T_{i+1}^j + h_s \delta T_i^j) + (1 - \frac{2ah_s\tau}{\lambda_s \delta})T_i^j \\
T_i^{j+1} &= \frac{2a\tau}{\delta^2} (T_{i-1}^j + h_s \delta T_i^j) + (1 - \frac{2ah_s\tau}{\lambda_s \delta})T_i^j
\end{align*}
\]  

(11)

The results of simultaneous equations (10) and (11) are as follows

\[
\begin{align*}
T_i^{j+1} &= 2F(T_{i+1}^j + B_i T_i^j) + (1 - 2B_i F - 2F)T_i^j \\
T_i^{j+1} &= F(T_{i+1}^j + T_{i-1}^j) + (1 - 2F)T_i^j \\
T_i^{j+1} &= 2F(T_{i+1}^j + B_i T_i^j) + (1 - (1 - 2B_i F - 2F))T_i^j
\end{align*}
\]  

(12)

Where, \( F = \frac{a\tau}{\delta^2} \), \( B_i = h_s \delta \lambda_i / \lambda_s \), \( B_s = h_s \delta / \lambda_s \). Equation (12) is the mathematical model for heat transfer calculation of barrel.

4. Numerical calculation of barrel heat transfer

The calculation process of gun barrel heat transfer is based on MATLAB. The time step is \( 10^{-4} \) s, and the space step is \( 2 \times 10^{-4} \) m. Take 0 # charge as an example for analysis. The temperature distribution in 0.2 s of single shot is shown in Figure 4. It can be seen from Figure 3 and Figure 4 that the inner wall temperature rises rapidly at first, and the speed of temperature increase gradually decreases; when the inner wall temperature reaches the extreme value, it decreases rapidly, and the speed of temperature decrease gradually; the gradient of temperature on the radial axis is very large, and the local temperature gradient exceeds \( 10^6 \) K/m. The temperature distribution of the gun firing 10 rounds continuously at the frequency of 10s is shown in Figure 5 and Figure 6.

![Figure 3. Temperature distribution under single shooting](a)
The following conclusions are drawn from Figure 5 and Figure 6 and the calculation results, (1) In the next shot, the inner wall has a higher initial temperature, so the peak temperature caused by the next shot will be increased. The results show that: with the firing going on, the increase range of the peak temperature is smaller and smaller. (2) During continuous firing, the temperature at a certain depth in the radial direction of the barrel fluctuates, and the fluctuation amplitude decreases with the increase of the depth. (3) In the radial coordinates of the barrel, the temperature does not necessarily decrease monotonically. Under certain circumstances, one or more extreme points may appear. (4) With the firing going on, the more heat is stored in the barrel. Therefore, the inner wall temperature drops faster in single shot than in continuous multiple shot.

5. Conclusions
With the help of classical interior ballistic model, the thermal environment parameters inside and outside the gun barrel are analyzed and calculated. The mathematical model of barrel heat transfer calculation and numerical calculation of barrel heat transfer are carried out. The results show that the inner wall temperature increases rapidly at first, and the speed of temperature increase gradually decreases when the inner wall temperature reaches the extreme value, and the speed of temperature decrease gradually; when the inner wall temperature reaches the extreme value, the temperature does not necessarily decrease monotonically in the radial coordinates of the barrel, and one or more extreme points may appear under certain circumstances.

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