Numerical simulation of 3D barrel system based on thermal-structural coupling under continuous firing

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Abstract. In order to study the laws of temperature field and deformation field of the 5.56mm rifle under continuous firing, the barrel system was taken as the research object, the transient temperature field and the deformation field of the 3-D barrel system under continuous firing of 150 rounds was calculated by using thermal-structural coupling method based on ANSYS. The temperature of multiple positions of the combat gun that partially removed the lower handguard was measured by the thermal imager. The difference between the test results and the simulation results was kept below 20%. The results of simulation and experiment showed: (1) The peripheral parts of the barrel have important influence on the temperature field and deformation field of the barrel system, and it is not negligible for the study of the thermal effects of combat gun under continuous firing. (2) The temperature of the inner wall increases with the number of projectiles under continuous firing, and the chromium layer has a significant effect of reducing thermal pulse. (3) Because the barrel is heated more unevenly, it will increase the inner diameter of the barrel and offset the axis. In a word, studying and analyzing the laws of temperature field and deformation field of the rifle can lay the foundation of the thermal management theory of firearms.

1. Introduction
The phenomenon that the accuracy of fire decreases due to the heat transfer of the barrel is a common problem of automatic rifles in service at home and abroad. In the process of continuous firing, the high temperature generated by the burning of powder can reach almost 3000 °C, and the high-speed flowing powder gas releases heat to the inner wall by forced convection and radiation, which results in a significant decrease in the mechanical properties of barrel materials. The chromium layer in the inner wall falls off, cracks and breaks during the process of high frequency and high-temperature powder gas scouring and projectile squeezing. With the increase of barrel temperature, the inner wall is severely ablated and worn, which is the result of the combined effects of the thermal, chemical and projectile mechanical friction of the powder gas, where thermal plays a leading role [1-4]. At present, most authors only use the barrel as a simulation model for temperature and deformation research. The research results caused by neglecting the influence of peripheral parts on the barrel are more suitable for ballistic guns than combat guns. Therefore, the mechanism of heat transfer of the combat guns is still unclear.
The studies on heat transfer of the barrel are as follows. Wu [5] expounded the causes of wear and burn, and proposed that the body fluid cooling technology is an effective method to solve this problem. The heat transfer of 155 mm midwall cooling composite gun barrel was analyzed theoretically and the theoretical analysis was verified by finite element analysis (FEA). Şentürk [6] proposed the interior ballistic solution of a 7.62mm barrel based on the firing test of the ballistic gun and G3 automatic rifle. The 3-D transient heat transfer and stress analysis were carried out by using the thermal-mechanical coupling theory. Işık [7] determined the 7.62mm barrel temperature distribution and cook-off time through various firing tests and used a thermal imager to measure the outer surface temperature of the hottest area on the combustion chamber. The temperature distribution of the inner wall/outer surface of the combustion chamber was created and analyzed using the ANSYS 14.5 Academic finite element solver. Finally, various parameters affecting the powder roasting time were analyzed. Değirmenci [8] determined the combustion characteristics of double-base powders with different particle sizes and initial temperatures by performing a series of firing tests and establishing a thermomechanical model of ABAQUS. Chung [9] created a new erosion formula, which can calculate the erosion rate of the gun barrel more accurately. Hill [10] established the heat transfer model of the transient temperature field of the barrel, which can effectively solve the heat management problem, and achieve the purpose of reducing the weight of the barrel and increasing its service life. Chen [11] proposed an input estimation method for recursively estimating the time-varying heat flux and wall temperature in the chamber. Mishra [12] developed a new transient thermal model for the barrel, which was used to calculate the temperature change of the barrel with time and was verified by experiments. Huang [13] used the finite element method to study the thermal effect of the 5.56mm ceramic barrel during firing. Predecessors have conducted in-depth discussions on the thermal effects of the 2D barrel, but it is rare to analyze and study the 3D barrel system.

The heat of the rifle is derived from the inner wall of the barrel, and the heat in the inner wall is mainly caused by the powder gas and the friction of the projectile. The heat transfer of the powder gas is much larger than the heat of friction between the projectile and the inner wall, so it can be neglected. At the same time, when studying the thermal effect of the rifle under continuous firing, many authors often use the test of the combat gun and the numerical simulation of ballistic guns to compare and verify. Although it reflects the variation laws of the temperature field and deformation field and has high research value. However, the influence of the peripheral parts of the barrel on the temperature field and deformation of the barrel is neglected. Compared with the traditional barrel heat transfer model, this paper aims to establish a more complete 3-D barrel system heat transfer simulation model, the sequential coupling method is used to calculate the transient temperature and deformation, and the temperature of multiple positions of the combat gun was measured by the thermal imager to verify the simulation results. A 3-D hexahedral mesh model of the barrel system was established in Hypermesh. The mesh type was defined and imported into ANSYS. The thermal-structural coupling of the barrel system was numerically simulated by the APDL command. Studying and analyzing the heat transfer of the rifle can lay the foundation of the thermal management theory of firearms.

2. Barrel system modeling

2.1. Model assumption
1. The combustion of powder accords with the law of geometric combustion.
2. Gravity is neglected.
3. The rifling is neglected and the barrel caliber is used as the inner wall diameter of the barrel, and the chromium plating on the surface of the inner wall is considered at the same time.
4. The Cr layer is in close contact with steel without considering contact thermal resistance.
5. The process of projectile extrusion in inner wall is neglected.
2.2. Theoretical formulation

According to the different physical states during the firing process of the projectile, each projectile in the continuous firing process is divided into three periods: interior ballistic period, aftereffect period and interval period. The powder gas transfers heat to the outer surface of the barrel through the chrome layer in the form of forced convection and thermal radiation. The outer surface of the barrel transfers heat to the peripheral parts through heat conduction, while the barrel and the peripheral parts carry out heat convection and radiation with the surrounding environment. Because the temperatures and coefficients of forced convection are different in each inner wall position of the barrel during the flight of the projectile, different theoretical formulas are used for calculating the coefficients of forced convection and temperature of the powder gas in each stage.

![Figure 1](image)

Figure 1. Heat transfer from the inner wall to the peripheral parts.

2.2.1. Barrel system boundary conditions and initial conditions

1) Initial conditions

   It is known that the temperature at the beginning of the firing is instantaneously distributed throughout the barrel:

   \[ T \big|_{t=0} = T_0 \]  

   Where \( T_0 \) is ambient temperature.

2) Boundary conditions of inner and outer surface of barrel system

   Combined with the heat transfer problem of the barrel, it meets the third type of boundary conditions [14].

   Inner wall boundary conditions:

   \[ h_a \left[ T_g(t) - T_{inner}(t) \right] \big|_r = -\lambda \frac{\partial T}{\partial r} \big|_r \]  

   Where \( h_a \) is composite heat transfer coefficient between powder gas and barrel, \( T_g \) is temperature of the gas in barrel, \( T_{inner} \) is inner wall temperature, \( \lambda \) is thermal conductivity of the barrel material.

   Outer surface boundary conditions:

   \[ C_{1,2} \left[ T_{outer}^4(t) - T_0^4 \right] \big|_r + h_b \left[ T_{outer}(t) - T_0 \right] \big|_r = -\lambda \frac{\partial T}{\partial r} \big|_r \]  

   Where \( C_{1,2} \) is system radiation coefficient between two surfaces, \( h_b \) is composite heat transfer coefficient between ambient temperature and barrel, \( T_{outer} \) is outer surface temperature.
2.2.2. **Main parameters in the boundary conditions of the barrel system**

1) Inner wall gunpowder gas temperature [15-16]

① Internal ballistic period

The formula of the powder gas temperature during the internal ballistic period is as follows:

\[ T_m(t) = \left[ 1 - \frac{(k-1)\phi qv^2}{2fw\varphi} \right] T_b \]  

(4)

Where \( k \) is thermodynamic coefficient, \( \phi \) is virtual coefficient, \( q \) is the quality of projectile, \( v \) is the speed of projectile, \( f \) is propellant power, \( w \) is charge weight, \( \varphi \) is percentage of powder burning, \( T_b \) is explosion temperature.

② Aftereffect period

The formula of the powder gas temperature during aftereffect period is as follows:

\[ T_m(t) = T_h \cdot e^{-At^\beta} \]  

(5)

Where \( T_h \) is average temperature of powder gas at the beginning of the aftereffect period, \( A \) and \( B \) are parameters fitted according to the experiment.

③ Interval period

There is no powder gas in the interval period, and the temperature in the barrel is ambient temperature.

2) Heat transfer coefficient of inner wall

① Internal ballistic period

During the interior ballistic period, the heat exchange between the high temperature powder gas and the inner wall of the barrel is mainly forced heat convection, accompanied by a small amount of radiation heat exchange. In order to simplify the calculation, it is assumed that there is only forced convective heat release between the powder gas and the inner wall of the barrel, and then the calculated convective heat release coefficient is properly modified to obtain the radiation heat release coefficient. Considering that the composite heat transfer coefficient of forced convection and radiation is:

\[ h(t) = h_c(t) + h_r(t) = K_c h_c(t) = \frac{0.023K(t)K_c}{d} Re^{0.8} Pr^{0.4} \]  

(6)

where \( h_c(t) \) is convective heat transfer coefficient, \( h_r(t) \) is radiation heat transfer coefficient, \( Re \) is the Reynolds number, \( Pr \) is the Prandtl number, \( K \) is thermal conductivity, \( K_c \) is correction factor, \( d \) is the barrel caliber.

② Aftereffect period

In the effective period after firing, the heat exchange between the high temperature powder gas and the inner wall of the barrel is forced heat convection, and the convection heat transfer coefficient formula of powder gas is as follows:

\[ h_c(t) = 0.02 \left[ \frac{v' \rho(t)}{2\mu(t)} \right] \rho(t) \frac{v'}{2} c(t) \]  

(7)

where \( \rho \) is density of powder gas, \( v' \) is the average velocity of gas during flow, \( \mu \) is dynamic viscosity of powder gas, \( c \) is specific heat capacity of powder gas.

③ Interval period

During the firing interval, the inner wall of the barrel is radiated to the atmosphere by natural convection. The natural convection heat transfer coefficient can be obtained by using the similarity principle, and the formula is as follows:
\[ h_c = C \left( \frac{G_r P_r}{\rho} \right)^m \lambda / d \]  

(8)

Where \( C \) and \( m \) are fitting coefficient, \( G_r \) is the Grashof similarity criterion, \( \lambda \) is thermal conductivity of air.

3) Heat transfer coefficient of outer surface

The heat transfer between the outer surface of the barrel system and the atmosphere is mainly natural convection and radiation heat transfer. Formula 8 can be used for natural convection heat transfer, and the radiation heat transfer formula\[17\] is as follows:

\[ h_r = \frac{\varepsilon C_b \left( \frac{T_{outer}}{100} \right)^4 - \left( \frac{T_0}{100} \right)^4}{T_{outer} - T_0} \]  

(9)

Where \( \varepsilon \) is effective emissivity, \( C_b \) is absolute blackbody radiation coefficient.

4) Gas port temperature and heat transfer coefficient

When an automatic rifle is fired, a small amount of powder gas in the inner wall enters the chamber through the gas port when the projectile is squeezed through the gas port, as shown in figure 2. In the simulation of the temperature field, the temperature and heat convection coefficient at the junction between the gas port and the inner wall of the barrel with a certain correction coefficient are taken on the inner wall of the chamber.

![Figure 2. Schematic diagram of powder gas flow through the gas port.](image)

3. Experiment and Numerical Model

3.1. Model Description

The barrel system is meshed using the Hypermesh tool. Since more than 99.9% of the mesh of the barrel system uses hexahedral mesh and a small amount of tetrahedral mesh is used in the local area of the gas port, the calculation element selects hexahedral element which can be reduced to tetrahedral or prism. The SOLOD70 element is used in the thermal calculation and the SOLOD185 element is used in the structural calculation. According to the number of different grids, the influence of peripheral parts on the heat transfer of the barrel and the solution time, the model of barrel system is divided into 135280 hexahedral elements and 161907 nodes based on the influence of different meshes, peripheral parts on heat transfer of gun barrel and the consideration of solving time. Considering the strong effect of the chromium layer on reducing the peak heat pulse of high-temperature powder gas, the chromium layer is divided into two layers of grid elements. Figure 3 is a 3-D model of the barrel system, and figure 4 is a 3-D hexahedral mesh model of the barrel system. 1 to 7 are verification model nodes or areas of the barrel system in figure 4.
3.2. Material Model
The barrel system calculated in this paper mainly includes two kinds of materials: (1) the inner wall of the gun is the Chromium layer; (2) the rest of the steel body is alloy steel material. Referring to [18][19], it can be seen that temperature has an important influence on the physical and mechanical properties of materials. The physical parameters that have influence on the heat transfer of the barrel system mainly include: $k$ is thermal conductivity, $c$ is specific heat capacity, $\rho$ is density of the material, and the physical parameters that have influence on the structure of the barrel system mainly include: $E$ is elastic modulus, $\mu$ is Poisson's ratio, $\alpha$ is thermal expansion coefficient. The specific material parameters are shown in tables 1:

Table 1. Basic physical parameters of materials.

| Material | $T/Â°C$ | $k/W\cdot m^{-1}\cdot K^{-1}$ | $c/J\cdot kg^{-1}\cdot K^{-1}$ | $\mu$ | $E/Mpa$ | $\alpha/K^{-1}$ | $\rho/kg\cdot m^{-3}$ |
|----------|---------|-------------------------------|-------------------------------|-------|---------|----------------|----------------|
| Chromium | 0 ~ 1200 | 83.8                          | 505.3                         | 0.3   | 200e3   | 9.4e-6         | 7191           |
|         | -273    | 34.8                          | 460.0                         | 0.289 | 209e3   | 1.25e-5        | 7801           |
|         | 20      | 33.8                          | 480.3                         | 0.29  | 207e3   | 1.25e-5        | 7801           |
|         | 300     | 32.0                          | 538.2                         | 0.295 | 200e3   | 1.25e-5        | 7801           |
|         | 600     | 31.0                          | 595.1                         | 0.3   | 182e3   | 1.25e-5        | 7801           |
| Steel   | 900     | 30.5                          | 634.2                         | 0.316 | 162e3   | 1.25e-5        | 7801           |

3.3. Model validation
The firing test specification is based on the comprehensive life test of automatic rifle in GJB4104.1-2000 standard: 150 rounds of firing with 5 magazines. The cooling cycle firing method is single-fire/point-fire/ continuous-fire, and the ratio of the projectiles is 1:7:2. It takes about 86s to complete 150 rounds. The test firing specification is shown in figure 5.
There are two main factors that affect the heat transfer: first, the structure of the weapon and ammunition, the performance of powder, manufacturing accuracy; second, the impact of external conditions such as shooters, meteorology, geography and other external conditions on the firing [20]. Therefore, during the test, the automatic rifle is fixed on the working platform through the rifle rack and the same batch of bullets are used to fire continuously in the indoor 100-meter target channel according to a certain firing specification, which can eliminate the influence of external factors and quantitatively analyze the influence of thermal effects. The schematic installation of automatic rifle and test equipment is shown in figure 6:

![Figure 5. Firing specification.](image)

![Figure 6. Schematic installation of automatic rifle and test equipment.](image)

In the process of continuous 150 rounds, 1 to 7 are verification model nodes or areas of the barrel system in figure 4, the specific position is shown in figure 4. The maximum temperature difference of node 1 is 14.4%, the maximum temperature difference of node 2 is 15.0%, the maximum temperature difference of node 3 is 17.1%, the maximum temperature difference of node 4 is 19.6%, the maximum temperature difference of node 5 is 3.9%, the maximum temperature difference of node 6 is 16.0%, the maximum temperature difference of node 7 is 15.2%. On the whole, the difference between the experimental value and the calculated value is less than 20%, and the reliability is good, which accords with the theoretical study of the thermal effect.
### Table 2. Validation data.

| nodes | 30 rounds | 60 rounds | 90 rounds | 120 rounds | 150 rounds |
|-------|-----------|-----------|-----------|------------|------------|
| test value | 107.20 | 161.66 | 209.18 | 249.70 | 288.07 |
| calculated value | 91.73 | 142.48 | 191.01 | 236.93 | 288.85 |
| difference | 14.4% | 11.9% | 8.7% | 5.1% | 0.3% |
| test value | 146.38 | 220.99 | 286.75 | 343.96 | 395.05 |
| calculated value | 124.37 | 205.77 | 277.30 | 340.49 | 403.54 |
| difference | 15.0% | 6.9% | 3.3% | 1.0% | 2.1% |
| test value | 178.83 | 270.11 | 354.28 | 410.44 | 475.95 |
| calculated value | 148.17 | 241.20 | 324.57 | 399.52 | 476.47 |
| difference | 17.1% | 10.7% | 8.4% | 2.7% | 0.1% |
| test value | 209.10 | 302.68 | 376.41 | 439.84 | 520.01 |
| calculated value | 168.09 | 270.45 | 362.21 | 444.96 | 531.35 |
| difference | 19.6% | 10.6% | 3.8% | 1.2% | 2.2% |
| test value | 182.10 | 271.07 | 347.87 | 412.38 | 473.69 |
| calculated value | 180.33 | 264.88 | 334.16 | 396.11 | 478.91 |
| difference | 1.0% | 2.3% | 3.9% | 3.9% | 1.1% |
| Gas port | 80.10 | 119.20 | 154.92 | 208.21 | 240.24 |
| test value | 67.27 | 110.26 | 149.74 | 193.05 | 223.89 |
| calculated value | 16.0% | 7.5% | 3.3% | 7.3% | 6.8% |
| Rear sight base | 11.01 | 12.21 | 13.85 | 15.37 | 17.20 |
| test value | 10.02 | 11.15 | 12.99 | 13.04 | 15.41 |
| calculated value | 9.0% | 8.7% | 1.0% | 15.2% | 10.4% |

### 4. Results and discussion

#### 4.1. Temperature field analysis

The material properties, boundary conditions and the secondary definition of the solver are added to the barrel system in ANSYS. The 3-D temperature field of the barrel system is calculated. The simulation results are compared with the experimental results. The simulation results are in good agreement with the experimental results, and the verification data are shown in Table 2.

Firing 150 rounds continuously, the temperature field changes in the high-temperature area as shown in figure 7. The simulation results show that with the increase of the number of projectiles, the high-temperature area of the barrel is transferred from the tail to the middle of the barrel, and the high-temperature position is basically stable at about 110 mm from the tail of the barrel. The result is basically consistent with the temperature field distribution of the combat gun captured by the infrared thermal imager after 150 rounds. It can be clearly seen that the heat from the inner wall of the three areas of A/B/C in figure 7 is partially absorbed by the peripheral parts, and as the amount of projectile increases, the temperature of the peripheral parts rises obviously. Therefore, it is known that the heat absorbed by the peripheral parts from the barrel is the main reason for the transfer of the high-temperature area of the barrel.

Figure 8 shows the temperature change of inner wall and outer surface at high temperature position with time. After 150 rounds of continuous firing, the inner wall temperature of the barrel at high temperature can reach 950 °C and quickly drop to 540 °C. At the same time, figure 8 shows that due to the excellent material properties of the chromium layer, when the temperature reaches the chromium-steel interface through the inner wall, the thermal pulse decreases by half.

Figure 9 shows the temperature change of the inner wall and the outer surface at the muzzle with time. After 150 rounds of continuous firing, the inner wall temperature of the barrel at high
temperature can reach 305 °C and quickly drop to 220 °C. At the same time, figure 9 also shows that due to the excellent material properties of the chromium layer, when the temperature reaches the chromium-steel interface through the inner wall, the thermal pulse decreases by half.

The curve of the temperature of the inner wall along the axis of the barrel is shown in Figure 10. In figure 10, it can be clearly observed that the temperature is lower than the temperature of the surrounding nodes in 232 mm and 384 mm from the tail of the barrel. The main reason is that the two positions of the barrel are respectively connected with the air chamber limiting seat and the bayonet seat, and the peripheral parts absorb the heat from the barrel through heat conduction, which causes more uneven heating of the barrel at different positions.

Figure 7. Trend of high temperature area transfer.

Figure 8. Temperature variation at high-temperature position.

Figure 9. Temperature variation at muzzle.
4.2. Deformation field analysis

The calculation results of the deformation field based on the thermal-structural coupling are as follows:

Figure 11 reflects the change in the radial diameter of the eight sections of the inner wall on the barrel. In general, the inner diameter of the barrel increases with the increase of the number of projectiles. Except for the restraining of the tail of the barrel, the diameters of the other sections are expanded to different degrees. However, due to the heat absorption of the peripheral parts of the barrel, the deformation of the inner wall at the 232mm and 384mm of the tail of the barrel is lower than that of the nearby part.

Figure 12 shows the radial offset of the barrel axis of eight different sections. The radial offset of the barrel under the thermal load is analyzed by fixing the tail of the barrel. It can be seen from the figure that the axis of the barrel along the radial direction has a tendency to descend first and then rise, which inevitably leads to the difficulty of squeezing into the movement of the projectile, thereby causing a phenomenon of speed loss.

In combination with figure 11, figure 12 and previous research results on the ballistic guns, though the diameter of each cross-section of the barrel is increased significantly by binding the tail of the barrel, the axis of the barrel is still in the initial position. However, compared with the ballistic guns, combat guns have more peripheral parts, which have a restraining effect on the thermal deformation of the barrel. Although the inner diameter still increases with the number of projectiles, the position of the barrel axis has changed significantly.
5. Conclusion
In this paper, based on ANSYS, a relatively complete barrel system heat transfer model is established by using the research methods of theory, experiment, and simulation. By analyzing the laws of the temperature field and the deformation field of the barrel, it lays the foundation for the theory of firearm thermal management. The specific conclusions are as follows:

1) The peripheral parts of the barrel have an important influence on the temperature distribution of the barrel, which directly affects the distribution of the high-temperature area inside the barrel.
2) Under continuous firing, the inner wall temperature increases as the number of projectile increases. At the same time, the chromium layer has a significant effect on reducing thermal pulse.
3) Under continuous firing, the thermal expansion and bending deformation of the barrel caused by uneven heating are more serious, which is mainly manifested by the increase of the inner diameter of the barrel and the deviation of the axis. It will inevitably make it more difficult for the warhead to squeeze into the inner wall and more serious wear of the inner wall.

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