Heat Transfer Simulation of Large Caliber Gun Barrel

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Abstract—During the continuous firing of artillery, the inner wall of the barrel will experience a continuous rise of temperature, which has much to do with the ambient temperature and the way it cools. For artillery using combustible cartridge, the temperature rise of the barrel’s interior wall will have a great impact on the safety of combustible cartridge during successive shots. The finite element model of gun barrel was established by ANSYS software while the convection heat transfer in the inner and outer walls of the barrel and the heat transfer in the barrel wall were simulated. This paper observed the temperature variation of the inner and outer wall of the barrel under different ambient temperatures and different cooling methods, revealing that the higher the ambient temperature, the faster the barrel temperature rises. Different cooling methods have little influence on the inner wall temperature, which would emerge long after shooting. The research provided theoretical basis for the safe use of combustible cartridge cases.

1. Introduction
As the core of fire coverage and suppression, artillery is known as “God of War”. It is necessary to improve the accuracy and firing rate of artillery in modern wars. However, under continuous and rapid firing, high-temperature and high-pressure gunpowder gas flows at a high speed inside the barrel of artillery, thus overloading the barrel. The temperature gradient between gunpowder gas and the barrel would inevitably generate heat exchanges between the two, causing the barrel to be heated instantly. For artillery using combustible cartridge, the temperature rise of barrel’s inner wall during continuous firing could pose potential safety hazard from the combustible cartridge. The effect will be further amplified with the rising firing rate of the artillery. Therefore, barrel heating has always been an important topic in researches of artillery technologies. This paper used ANSYS finite element program for numerical simulation on the transient thermal response of gun barrel during firing to observe the impact of different ambient temperatures and different cooling methods on the temperature rise of barrel, and to analyze how barrel heating would affect the safety of combustible cartridge cases during firing.

2. Theoretical Analysis of Heat Transfer in Barrel

2.1 Transient heat transfer model of barrel
Ignoring the friction of the projectile on the bore wall and its thermal effect. Ignore the radiation heat transfer and expand the convection heat transfer coefficient to compensate for the neglected radiation heat transfer. Ignoring the axial heat transfer in the barrel wall. The temperature field has axial and angular symmetry. Therefore, the heat transfer of the barrel can be simplified as one-dimensional heat transfer. The simplified one-dimensional transient heat conduction equation is given by:

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)
\]
where: $T$ is the temperature at which the barrel is fixed to the wall; $t$ is time duration; $r$ is the distance from a certain point in the barrel to the symmetry axis of the barrel; $\alpha$ is the thermal conductivity coefficient of the barrel. At this point, the temperature distribution is only a function of the barrel radius $r$ and time $t$, i.e. $T=T(r,t)$.

2.2 Transient heat transfer model of barrel taking coolant into account

The gun barrel containing coolant can be regarded as a double-tube structure, where there are forced convection heat exchanges between the inner wall of the barrel and gunpowder gas. There are also forced convection heat exchanges between the outer wall of the inner tube and the coolant. As the coolant is in a flowing state, its temperature can be regarded as fixed, thus allowing the heat transfer between the coolant and the outer tube to be ignored.

3. Initial and Boundary Conditions of Barrel

3.1 Interior ballistic trajectory

Motion equation of projectile in-bore:

Energy conservation equation:

$$\omega \psi R T = f \omega \psi - \frac{\theta \rho m v^2}{2}$$

Projectile motion equation:

$$\varphi m \frac{d\psi}{dt} = SP$$

The relation between projectile speed and stroke:

$$\frac{dl}{dt} = v$$

By combining the above equations, the interior ballistic equation is given by:

$$\psi = \begin{cases} \chi Z (1 + \lambda Z + \mu Z^2) & Z < 1 \\ \chi_s Z (1 + \lambda_s Z) & 1 \leq Z < Z_k \\ 1 & Z \geq Z_k \end{cases}$$

$$\frac{dZ}{dt} = \begin{cases} \frac{u_1}{e_3} p^n & Z < Z_k \\ 0 & Z \geq Z_k \end{cases}$$

$$\frac{dl}{dt} = v$$

$$\frac{dv}{dt} = SP$$

$$\frac{d\psi}{dt} = \frac{\varphi m}{\varphi}$$

$$SP (l_\psi + l) = f \omega \psi - \frac{\theta}{2} \rho m v^2$$

where $\psi$ is the percentage of gunpowder burned; $\chi, \lambda, \chi_s$ and $\lambda_s$ are characteristic quantities of gunpowder shape; $Z$ represents the relative burnt thickness of gunpowder; $Z_k = \frac{e_k + \varphi}{e_3}$ is the relative combustion thickness at the end of gunpowder combustion; $\mu_1$ is the burning rate coefficient of gunpowder; $n$ is the pressure index; $P$ is the gas pressure gunpowder; $\varphi$ is the secondary work factor; $m$ is the mass of the projectile; $f$ refers to gunpowder force; $\omega$ is the charge; $l_\psi$ is the free volume hole size of the chamber; $\theta$ is the thermodynamic parameter of propellant.

Based on the definition of energy conservation equation and gunpowder force:
The average temperature in the bore during the interior ballistic process is calculated by:

\[ T = T_v - \frac{\theta \varphi m v^2}{2 \omega \psi R} \]

3.2 After-effect period

Formula for calculating temperature of propellant gas in the after-effect period:

\[ T = T_v e^{-At^B} \]

Where

\[ B = \ln \left( \ln \left( \frac{T_k}{T_v} \right) \right) / \ln \left( \frac{t_n}{t_n + t_h} \right) \]

\[ A = -\ln \left( \frac{T_k}{T_v} \right) / t_n B \]

\( T_k \) is the average temperature of gunpowder gas at the end of the interior ballistic process; \( t_n \) is the duration of internal ballistic process; \( t_h \) is the duration of the after-effect period; \( T_a \) is the average temperature of gunpowder gas in the barrel at the end of the after-effect period.

At present, the third kind of boundary condition is adopted for the inner boundary when shooting, which is more consistent with the actual situation. Heat Transfer Coefficient \( h_g(t) \) of propellant gas convection at the firing moment \( t \) is given by:

\[ h_g(t) = k \times 0.023 \frac{\lambda_g(t)}{d} \left( \frac{V_g(t) \rho_g(t) d}{\mu_g(t)} \right)^{0.8} \times \left( \frac{C_{pgg}(t) \mu_g(t)}{\lambda_g(t)} \right)^{0.4} \]

where: \( \lambda_g(t) \), \( V_g(t) \), \( \rho_g(t) \), \( \mu_g(t) \) and \( C_{pgg}(t) \) are the thermal conductivity, flow rate, density, viscosity coefficient, and specific heat of propellant gas at time \( t \) respectively; \( d \) is the caliber of the barrel. Considering the influence of rifling, wall roughness and neglected radiation heat transfer, \( k \) is set between 1.15 and 1.2.

The firing interval is regarded as the process of heat transfer via natural convection between the inner wall of the barrel and the air. The outer boundary conditions are regarded as heat exchanges between the outer wall of the barrel and the air under natural convection, or heat exchanges between the outer wall and the cooling liquid under forced convection. The heat dissipation coefficient of water to the barrel is given by:

\[ \alpha = 0.023 R_e^{0.8} P_r^{0.4} \frac{\lambda}{d} \]

where: \( R_e \) is the Reynolds number, \( P_r \) is the Prandtl number, \( \lambda \) is the thermal conductivity of water, and \( d \) is the equivalent diameter of the cooling groove.

4. Heat Transfer Simulation of Barrel and Analysis

This paper took the calculated boundary conditions of interior ballistic process, after-effect period and firing interval as input to simulate the heat transfer of 30-shot barrel under air-cooling and water-cooling conditions at different ambient temperatures for the section where the bottom of the projectile is located using the APDL module of ANSYS. The section grid is divided as shown in Figure 1. The curve of temperature changes at the end of shooting was obtained by simulation.
4.1 Influence of External Temperature on Heat Transfer of Barrel

The analysis revealed the law of temperature variation at nodes in the inner and outer wall under three different external temperature of -40°C, 25°C and 50°C, as shown in Figure 2-4, the curves from top to bottom in the figure correspond to nodes in the interior wall, the middle section of the barrel and the outer wall from top to bottom. As can be seen from the figure, continuous shooting shows increased volatility of temperature variation in the inner wall of the barrel with the increase of the number of projectiles fired. The highest temperature occurs during the firing of the last projectile, during which the middle section and outer wall show a slow rise in temperature while the highest temperature occurs at the last moment. The comparison shows that the ambient temperature has a greater impact on heat transfer of the barrel, and is more effective on the outer wall than the interior wall: under the condition of -40°C, the barrel reached 791k in the interior wall and 400k in the outer wall after 30 rounds; At 25°C, the inner wall reached a temperature of 837k and the outer wall reached a temperature of 468 K after 30 rounds. At 50°C, the number was 854k and 493k respectively.
Shootings taking place at different ambient temperatures would show differences in the intensity of convective heat transfer between the barrel and the air. The higher the ambient temperature, the lower the intensity of convective heat transfer, and the less the heat dissipated by the inner and outer walls of the barrel, thus accelerating the rise of barrel temperature. Therefore, ambient temperature affects the barrel temperature by changing the intensity of heat dissipation.

4.2 Influence of different cooling methods on heat transfer of barrel

The study revealed the law of temperature variation at the nodes in the inner and outer wall under air cooling and water cooling at normal temperature, as shown in Figure 5-6, where the curves from top to bottom in the figure correspond to nodes in the inner wall, middle section of the barrel, and outer wall. Similarly, the temperature of the interior wall of the barrel fluctuates with the increase of the number of projectiles fired during continuous firing. The highest temperature occurs during the firing of the last projectile, where the temperature of the middle section and outer wall rises slowly, and the highest temperature occurs at the last moment.
Comparison of the two figures shows that the cooling method has little impact when there are only a limited number of shots being fired. When 12 shots are fired continuously, the inner and outer wall temperatures are 655k and 321k under air cooling condition, and 656k and 313k under water cooling condition. As the number of shots increases, water cooling shows greater advantages: when 30 shots are fired continuously, the inner and outer wall temperatures are 837k and 468k under air cooling condition, and 826k and 378k under water cooling condition.

Air cooling and water cooling are categorized as natural convection and forced convection respectively. As the convective heat transfer coefficient of water cooling is much larger than that of air cooling, the water-cooling method affects the temperature of barrel via different forms of convective heat transfer during long continuous firing.

4.3 Influence of long successive firing on temperature of the interior wall

As can be seen from the figure, the temperature rise curve of the interior wall after each firing interval
is similar to a parabola. After 4 rounds, the temperature of the interior wall of the barrel reached 478k, exceeding 200℃. For artillery, it is very common to shoot more than 4 rounds in a row. Therefore, after 4 rounds in a row, the temperature of the interior wall is usually above 200℃ before the next round of ammunition is loaded after each shot. The water-cooling device has little impact on the temperature of the interior wall within a short time. Under the condition of water cooling, the temperature of the interior wall will reach above 200℃ after the 4th round, and would be even warmer under high temperature environment. Under the condition of water cooling, the interior wall temperature of the barrel reached 670k, close to 400℃ after 13 successive shots.

4.4 Safety of combustible cartridge in successive continuous firing
At present, the combustible cartridge has an ignition point of about 190℃, which could increase to 400℃ when coated with high temperature resistant substance. According to analysis in 3.3, the interior wall temperature of the barrel reached the ignition point of the combustible cartridge after 4 successive shots, and the temperature of the interior wall would exceed the upper limit of the high-temperature resistant coating of the combustible cartridge after 13 successive shots. Therefore, there is potential safety hazard in using the combustible cartridge at this stage when firing.

5. Conclusion
In this paper, the finite element model of the barrel was established using the software ANSYS. Considering the convection heat transfer of the inner and outer walls and heat transfer in the wall of the barrel, the paper analyzed the law of temperature variation of the barrel under different ambient temperatures and different cooling methods. It was revealed that with the increase of the ambient temperature in which the shooting takes place, the intensity of natural convection between the interior and outer walls of the barrel and the environment is weakened, with less heat loss of the barrel and faster rise of temperature. There are differences in the convective heat transfer coefficient between different cooling methods, with the coefficient of water significantly greater than that of the air. Therefore, water cooling can better control the temperature rise of the barrel compared with air cooling during successive firing. This paper serves as a reference for future studies on the safety of combustible cartridge case under temperature rise of the interior wall undergoing a long duration of firing. It also provides insights into the impact of environmental factors on weapon performance that should be fully considered in the design of weapons, thus ensuring the safety of combustible cartridge case and avoiding safety accidents when the thermal performance of combustible cartridge case is not fully known to scientists at this stage.

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