

Analysis of Thick-Walled Cylinder Temperature Field based on the Thermal-Fluid-Solid Coupling

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Abstract: The barrel is a special thick-walled cylinder. It is significance to study the temperature distribution of thick-walled cylinder under liquid-cooled state to weapon launch safety and effectiveness. Taking a naval gun barrel as research objective, a unified thermal-fluid-solid coupling model is put forward including barrel solid wall, the cooling water and the water jacket solid wall. The unsteady coupled temperature field of the barrel is calculated at the time of single and continuous firing and some influencing factors such as cooling water flow velocity, barrel wall thickness and so on, are analyzed to the barrel temperature field. The results show that the water cooling effect of the barrel outer is closely related to the wall thickness and the cooling water flow velocity. When the barrel wall thickness is small, increasing the flow velocity increase heat dissipation and reduce barrel wall temperature obviously. When the barrel wall thickness is large, the water cooling effect depends on the total cooling time and small correlation with the velocity of cooling water flow.

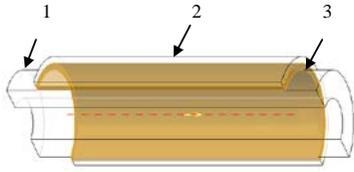
Keywords: Temperature, thermal-fluid-solid, thick-walled cylinder

INTRODUCTION

The barrel is a special thick-walled cylinder and it is one of the most important parts of the weapon. In many factors that caused damage to the body chamber, heat is one plays a dominant, controlling role in those factors, it determines ablation life of the barrel. With the requirements of strong firepower and continuous shooting, the barrel burning serious impact on weapon performance, barrel life and institutions reliability and even threatened the striker safety (Yonghai, 2010; Shi-Chi and Tse-Yung, 1993; Copley and Tomas, 1974). It has been a great concern of the national military. As one of the most effective technology controlling barrel heat, water-cooled technology has been widely used in the shipborne small and medium caliber gun and ground-based antimissile small caliber automatic gun, such as the U.S. MK75 76mm gun and AGS155mm advanced gun system. From the perspective of physical fields, barrel by using of water-cooled technology, belongs to the thick-walled cylinder temperature field problem in the coupling effect of heat, the flow field and solid field. The thermal boundary conditions of the thick-walled cylinder is decided by the heat exchange process dynamically (Bundy *et al.*, 1993; Burton and South, 2004; Boisson and Grignon, 1993). The inner surface of thick-walled cylinder forced by the interaction constraints of the gunpowder gas and solid wall and the outer surface forced by the interaction constraints between cooling water and solid wall. Shi-Chi Chu assume barrel is finite-length thick-walled cylinder, take the inner wall convective heat transfer coefficient as a constant, obtained analysis solution of thermal-solid

coupling barrel temperature when single firing; Copley J.A calculated thermal-solid coupling temperature field of barrel using two-dimensional axisymmetric model when continuous firing; Bundy M.L. calculated interior ballistics and barrel coupling model of heat transfer using the finite difference method, temperature distribution of the barrel bore surface with a chromium layer was obtained. Taking a naval gun barrel as research objective, a unified thermal-fluid-solid coupling model is put forward including barrel solid wall, the cooling water and the water jacket solid wall. The unsteady coupled temperature field of the barrel is calculated at the time of single and continuous firing and some influencing factors such as cooling water flow velocity, barrel wall thickness and so on are analyzed to the barrel temperature field. Model and calculation method used in the study can also apply to other temperature field calculation of thermal-fluid-solid coupling thick-walled cylinder (Lawton, 2003).

In this study, the unsteady coupled temperature field of the barrel is calculated at the time of single and continuous firing and some influencing factors such as cooling water flow velocity, barrel wall thickness and so on, are analyzed to the barrel temperature field. The results show that the water cooling effect of the barrel outer is closely related to the wall thickness and the cooling water flow velocity. When the barrel wall thickness is small, increasing the flow velocity increase heat dissipation and reduce barrel wall temperature obviously. When the barrel wall thickness is large, the water cooling effect depends on the total cooling time and small correlation with the velocity of cooling water flow.



1 thick-walled cylinder (barrel) 2 Water jacket 3 Cooling water

Fig. 1: Schematic diagram of a thick-walled cylinder system

THICK-WALLED CYLINDER THERMAL-FLUID-SOLID COUPLING MODEL

The barrel of a naval gun system consists of a water jacket and thick-walled cylinder (barrel), using water to a succession of cooling between them. The heat transfer coupling process between barrel and cooling water include barrel heat conduction inside the solid wall, heat transfer between fluid flow and the solid wall and heat transfer inside the fluid flow. Figure 1 shows a schematic diagram of a thick-walled cylinder system. The mathematical model of the barrel system includes solid calculation region of the barrel and fluid calculation region of cooling water. The establishment of thermal-fluid-solid coupling model of the barrel can reflect the actual condition of the flow field and temperature field and couple of flow field and the solid wall of the barrel.

Flow and heat transfer control model of fluid domain: To calculate fluid heat transfer, Fourier's law is needed to follow while solving the mass equation, momentum equation and energy equation of fluid flow equations.

- **Fourier's law:**

$$\Phi = -kAgradT \quad (1)$$

where, Φ = The thermal conductivity of heat flow; A is the cross-sectional area perpendicular to the direction of heat flow; $grad$ is temperature gradient, "-" express the heat flow direction in the direction along the lower the temperature, contrary to the direction of temperature gradient.

- **Fluid control equations:** The cooling water flow is more complex movement of fluid turbulence. Reynolds decomposition and average method is used to decompose the dependent variable in the governing equations of fluid movement and then the Reynolds-averaged is conduct to the other factors of the control equation. The turbulent flow control equations are a set of partial differential equations, which contains the mass conservation equation, momentum conservation equation and energy conservation equations.

Mass conservation equation (continuity equation) is as follows:

$$\frac{\partial \rho}{\partial t} + div(\rho \cdot u) = 0 \quad (2)$$

Momentum conservation equations (Navier-Stokes equations) are as follows:

$$\begin{cases} \frac{\partial(\rho \cdot u)}{\partial t} + div(\rho \cdot u \cdot u) = div(\mu \cdot grad u) - \frac{\partial p}{\partial x} + S_{Mx} \\ \frac{\partial(\rho \cdot v)}{\partial t} + div(\rho \cdot v \cdot u) = div(\mu \cdot grad v) - \frac{\partial p}{\partial y} + S_{My} \\ \frac{\partial(\rho \cdot \omega)}{\partial t} + div(\rho \cdot \omega \cdot u) = div(\mu \cdot grad \omega) - \frac{\partial p}{\partial z} + S_{Mz} \end{cases} \quad (3)$$

Conservation of energy equation is as follows:

$$\frac{\partial(\rho \cdot i)}{\partial t} + div(\rho \cdot i \cdot u) = div(k \cdot grad T) - p \cdot div(u) + \Phi + S_i \quad (4)$$

where:

$$\Phi = \mu \left\{ 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial \omega}{\partial z} \right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial \omega}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial \omega}{\partial y} \right)^2 \right\} + k(\nabla u)^2$$

Fluid state equations are as follows:

$$\begin{aligned} P &= P(\rho, T) \\ i &= i(\rho, T) \end{aligned} \quad (5)$$

The flow state of the cooling water inside the barrel is turbulence. Due to the complexity of the turbulent flow, it is too difficult to solve the above equations directly. The solving method for the so-called averaged equations and turbulence model is often adopted in the engineering field, namely the turbulent flow is regarded as the superposition of time-averaged and pulsating flow. This method will average the control equation over the time and adopts turbulence model to express the effects of pulsatory flow. The additional equations about turbulence model are also solved at this point in general. Using the common $k-\varepsilon$ model solve following two equations.

Turbulence kinetic energy k equation:

$$\frac{\partial(\rho \cdot k)}{\partial t} + div(\rho \cdot k \cdot u) = div\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) \cdot grad k\right] - \rho \cdot \varepsilon + \mu_t \cdot P_G \quad (6)$$

Turbulent dissipation rate ε equation:

$$\begin{aligned} \frac{\partial(\rho \cdot \varepsilon)}{\partial t} + div(\rho \cdot \varepsilon \cdot u) &= div\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right) \cdot grad \varepsilon\right] \\ - \rho \cdot C_2 \cdot \frac{\varepsilon^2}{k} + \mu \cdot C_1 \cdot \frac{\varepsilon}{k} \cdot P_G \end{aligned} \quad (7)$$

where,

$$\mu_i = \rho \cdot C_\mu \cdot \frac{k^2}{\epsilon}$$

$$P_G = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2$$

where, u, v, w are the projection of velocity U in x, y and z -axis respectively, $U = ui + vj + wk$; i is the internal energy, $i = c \cdot T$ S_{Mx}, S_{My}, S_{Mz} are the source term; μ is the fluid dynamic viscosity; p is pressure; $C_\mu, \sigma_k, \sigma_\epsilon, C1, C2$ is constant; div is the divergence.

The control model of solid region temperature field: in the solid region, the energy conservation equation of temperature field of the body inner wall is as follows:

$$\rho c \frac{\partial T}{\partial t} - k \nabla^2 T = 0 \tag{8}$$

The processing of fluid solid coupled boundary: The second class or third class of boundary conditions is used in heat transfer boundary of fluid-solid interaction, the equations are as follows:

$$\begin{cases} q_w|_{solid} = q_w|_{fluid} \\ -\lambda \left. \frac{\partial T}{\partial n} \right|_{solid} = h(T_w - T_f)|_{fluid} \end{cases} \tag{9}$$

where,

q_w = The interfacial heat flux
 n = The wall outside the normal

T_w and T_f are cross interface temperature and its surrounding fluid temperature respectively.

The velocity boundary conditions of solid wall of fluid-solid coupling region is $U = 0$.

BOUNDARY CONDITIONS

Due to the solving problem is thermal-fluid-solid coupling, the barrel, the cooling water flow and water jacket to form a whole. Flow solid points in its interior, the interface does not need to set any boundary conditions. The boundary conditions given below are the overall boundary conditions:

- **Energy boundary conditions:** The energy boundary conditions include both the energy of the solid (body tube and water jacket) and also includes the energy of the fluid (cooling water). At the entrance of in the fluid, the inlet temperature of the fluid need to be given and its manifestations is the same with velocity. The solid boundary conditions need to specify the function of the temperature on the boundary or specified on the boundary heat flux or specified on the boundary temperature and heat flux coefficient. In barrel bore boundary conditions,

assuming that the barrel bore with gunpowder gases exist only forced convection heat transfer, by forced convection coefficient of the correction the radiation heat transfer compensates the gunpowder gases. Bore core flow for the two-phase flow interior ballistic model to calculate the temperature of the gas bore gunpowder load history and the forced convection coefficient, the results as shown below.

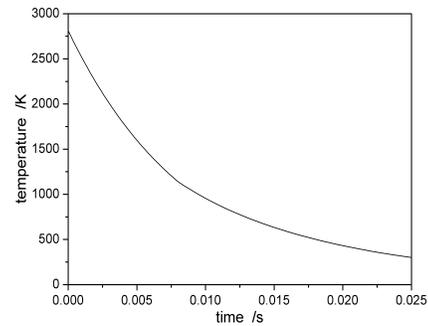
The outer wall region of the barrel which has no water to cool and the water jacket outer wall release heat by the form of natural convection and radiation heat, the boundary conditions:

$$h_2[T(t) - T_a] + \epsilon \sigma A [T^4(t) - T_a^4] = -k \frac{\partial T}{\partial n} \tag{10}$$

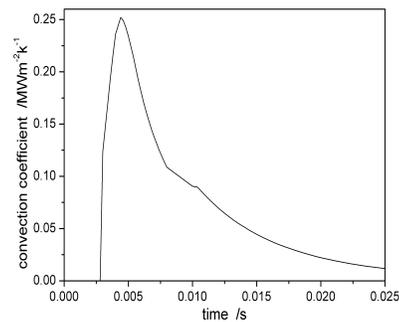
- **Momentum boundary conditions:** The momentum boundary condition refers to the fluid inlet and outlet conditions, usually expressed by the velocity or pressure.

The boundary conditions of the water at the entrance expressed by to the velocity: $V_x = 0, V_y = 0, V_z = 1.5\text{m/s}$.

The boundary conditions of the flow at the outlet expressed by the relative pressure: relative pressure is 0 (Fig. 2).



(a) Temperature load histories of gunpowder gas



(b) The forced convection coefficient of the gunpowder gases

Fig. 2: Barrel bore boundary conditions

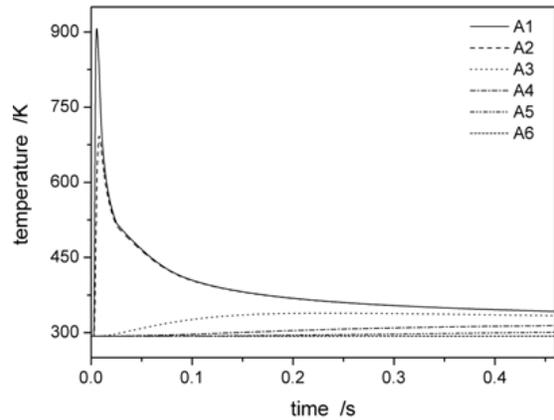
CALCULATION AND RESULTS ANALYSIS OF THE THICK-WALLED CYLINDER TEMPERATURE FIELD

The solution of the barrel coupling model is essentially solving a set of partial differential equations, using finite volume method to program for calculation. Barrel materials is 50BA, cooling water is sea water. In order to make the temperature field calculation more typical, selecting the end of the barrel 700 mm cross-sections to temperature analysis, A cross-section is located in rifling the starting area, where heat load is most concentrated. Select six points of the inner wall at A cross-section, the specific position in the Table 1, the A2 point in the surface of the combined chromium and steel.

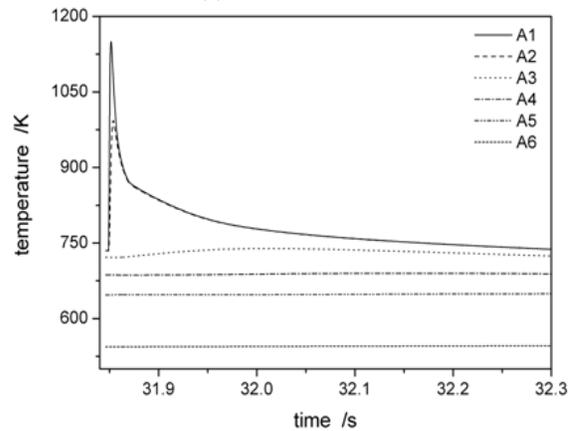
The specification for the shooting: 70 rounds bursts, shooting frequency for 130 rds/min, ambient temperature at 293 K, the water velocity of 1.5 m/s. It should be noted that, the RF 130 rds/min regarded the highest shooting frequency for the study and the actual firing below this value. Here taking the highest RF aims to highlight the main contradictions and reveal the effects of RF on the temperature of the barrel.

Single shooting, the barrel bore surface temperature response showed a pulse-like, rise to the peak within a very short time, followed by rapid decline. With the increases of heat dip toru depth, the temperature response amplitude of the rapid decay, the phase lag angle increases. When the depth reaches a certain value, the pulse peak disappeared and junction temperature showing the law of unilateral gentle rise. In Fig. 3a, chromium bore surface layer A1 point at 0.0056s, the temperature rose to 908.4 K, at 0.46154s, the temperature had dropped to 342.2 K; the A3 point, which located at the inner wall surface of a depth of 1.76 mm, The peak temperature is only 339.02 K; A4 point, which located at the inner wall surface of the depth of 3.52 mm, the temperature fluctuations have been very small; A5 point, which located at the inner wall surface of the depth of 5.28 mm, the temperature fluctuations disappeared on the whole. Continuous shooting, with the increase in the number of projectiles, single temperature pulse amplitude decreases gradually at the same time, the residual temperature values within the wall is a substantial increase. This is because the A1 point with bore gunpowder gas temperature difference gradually decreases with the increase in the number of projectiles, the heat absorbed gradually reduced, leading to the peak temperature pulse slowdown, at the same time, due to high RF, the heat spreads out very limited, a lot of heat gathered in the thin layer of the inner wall, resulting in

| The point of inner wall | A1 | A2 | A3 |
|----------------------------------|------|------|------|
| Distance from the inner wall/mm | 0 | 0.22 | 1.76 |
| The point of inner wall | A4 | A5 | A6 |
| Distance from the inner wall /mm | 3.52 | 5.28 | 10.5 |



(a) The first round



(b) The 70th round

Fig. 3: Barrel temperature of each point when single shooting

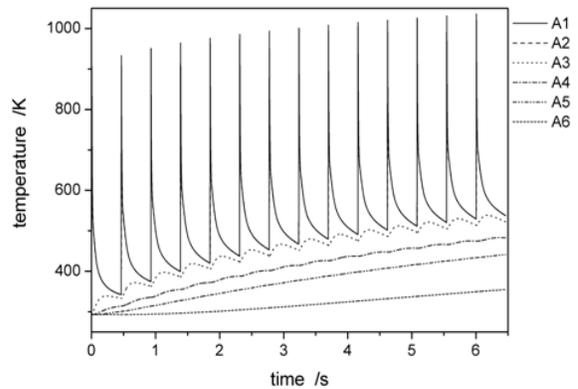


Fig. 4: Temperature changes over time when 14 rounds continuous shooting

the A1 point residual temperature rises rapidly, which further reduces the temperature difference with the airflow within the chamber. In Fig. 3, the maximum amplitude of the temperature pulse of first bullet is 615.4 K, the 35 rounds of the pulse maximum amplitude down to 456.6 K, closing 70 rounds, the pulse maximum amplitude is only 416.6 K. When the first round were fired upon, completion of the A1 point residual

temperature is 342.2 K; When 35 rounds fired is completed, the residual temperature of the A1 point rose to 647.1 K; closing 70 rounds, the residual temperature of the A1 point has reached 736.9 K. At the same time, the temperature values of the remaining points are also increased, but the rise is small compared with the A1 point.

When bursts, the temperature of the inner wall point of thin-layer response was uniformly periodic pulse-like rise. With the increase in the number of projectiles, the peak pulse temperature first and rapid increase, then gradually slowed down the law, the pulse amplitude gradually decreases, the pulse frequency and the frequency of the projectile are consistent. Radically outward along the cross section, Amplitude of the temperature response is drastically attenuated, severe changes regional focus in the barrel bore thin layer. In Fig. 4, A cross-section the second rounds of shells bore surface temperature of the peak increase of 26.5 K, to the 14th rounds of shells, the peak increase of only 4.7 K. After the 14 bursts, the pulse peak of the A1 point is 1036.4 K, pulse residual temperature is 537.6 K. A cross-section is located in the region of the beginning of the rifling, the thermal load is large, thus temperatures of inner bore are higher, the temperature fluctuations are large.

ANALYSIS OF THE RELATIONSHIP BETWEEN THE THICKNESS OF THICK-WALLED CYLINDER AND THE VELOCITY OF COOLING WATER

As the important variables affecting the temperature distribution, the thickness of barrel is closely related to the velocity of cooling water and has a complex effect on barrel temperature. To analysis the rules that thickness and velocity of cooling water act on barrel temperature field, the calculation program is modified to establish the computing model with wall thickness were, respectively 12, 18, 24, 30 and 36 mm, in which the velocity of cooling water were, respectively 0.5, 1.0, 1.5 and 4.5m/s with other settings remain unchanged. The results are shown in Fig. 5 to 7.

Heat storage method and radiating method are two feasible technical way for the control of barrel temperature rise rate. Heat storage method reduces the temperature rise rate of bore surface with most heat stored in the body tube by increasing the thermal capacity of the barrel. And then gradually dissipates and cooling over a long period of time after shooting. Increasing wall thickness is an effective measure to increase barrel thermal capacity. It can be seen from the Fig. 7, when the barrel wall thickness increased from 12 to 24 mm, the barrel bore surface residual temperature is decreased from 695.51 K to 639.97 K, which decreased

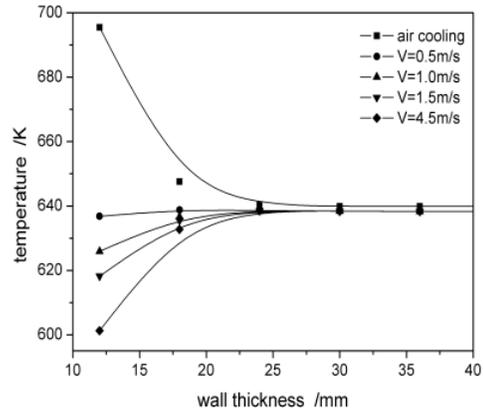


Fig. 5: Temperature effect curve of combination of wall thickness and flow velocity

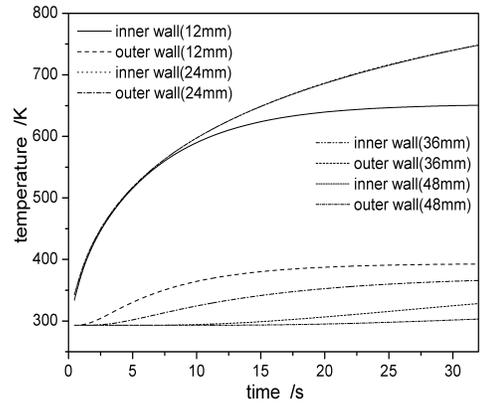


Fig. 6: Temperature curve of different wall thick section

by 8%. With a further increase in wall thickness, when the wall thickness reaches 30mm, bore surface residual temperature is decreased to 636.33 K with only 0.56% down. At the same time, the weight of barrel increases 32.6%. It has been very limited to control the barrel bore surface temperature by adding the wall thickness.

Heat radiating method reduces the temperature rising rate of barrel bore by increasing the heat released to outside environment. Tube external water cooling is obvious to barrel heat dissipation, but the cooling effect is closely related to the tube wall thickness to high rapid-fire weapons, as shown in Fig. 5. When continuous shooting with the tube wall thickness of 12 mm and the flowing velocity of 0.5 m/s, the tube bore surface temperature is reduced from 695.51 K by air cooling to 636.8 K; When flow velocity increases to 4.5m/s, the tube bore surface temperature is only 601.3 K, which is 13.5% lower than that cooling in air; The cooling effect will be more distinct while the cooling time is increased. When the wall thickness is increased to 18 mm, tube bore surface temperature with flowing velocity of 4.5 m/s reduces 14.86 K compared to natural air cooling, which is a drop of 2.2%. When the thickness

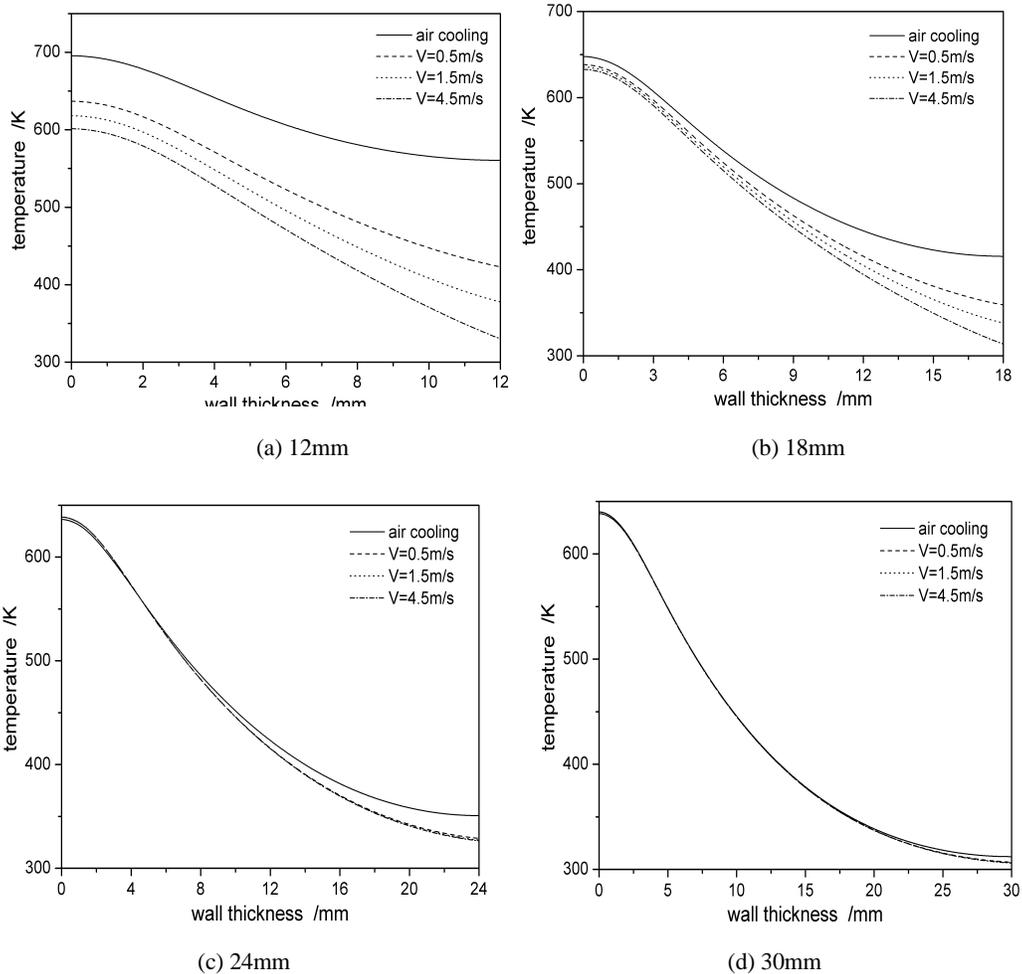


Fig. 7: The temperature distribution along the radial under the variation of wall thickness and flow velocity

is increased to 24 mm, tube bore surface temperature with flowing velocity of 4.5 m/s is only decreased by 1.8 K, which is a drop of 0.28%. The water cooling effect is negligible while the thickness increases further. Therefore, compared with the above two methods, for rapid fire weapon, when the tube with thin wall, the water cooling effect is better, the greater flow velocity the more cooling obviously; when the wall thickness is larger, the heat storage method has good cooling effect. Using water cooling tube, at the premise to meet the structural strength, it should adopt cooling solutions in the small wall thickness and big flow velocity at the premise to meet the structural strength.

Figure 6 is the temperature curve of different wall thick section. It is worth noting that the barrel bore peak temperature curves are coincident which the wall thickness are respectively 24mm, 36mm and 48mm. Initiated from 50 rounds, bore surface peak temperature increase is small and the curve tends to the straight. When gets to 70 rounds, the bore surface peak temperature curve with wall thickness of 12mm is still very steep and the bore surface temperature increases rapidly while the outer wall temperature curve tends to

the straight with a small increase. When the barrel with the wall thickness of 48mm gets to 70 rounds, the outer wall temperature increase is still smaller and there is little heat transferred to the outer wall because of short time.

Figure 7 is the temperature distribution curve along the radial under the variation of wall thickness and flow velocity. It can be seen from the figure, inner and outer wall temperature difference increases while the wall thickness is 12mm and using water cooling compared with air cooling. The faster the flow, the greater the temperature difference between the inner and outer wall. With the wall thickness increased, the temperature difference between inner and outer wall gradually increases; when the wall thickness increased to a certain value, increasing the flow velocity has brought a cooling effect, but the effect is not obvious.

CONCLUSION

In this study, the following conclusions are mainly gotten:

- A uniform temperature field coupling calculation model including barrel solid wall, the cooling water flow and water jacket solid wall is put forward in this study. By calculating the temperature response rules of the barrel at the time single and continuous firing is obtained, validity of barrel thermal-fluid-solid coupling model is confirmed. It provides theory and method of computing the temperature field for the water-cooled barrel
- The water cooling effect of the barrel outer is closely related to the wall thickness and the cooling water flow velocity. When the barrel wall thickness is thinner, increasing the flow velocity increased heat dissipation and reduce the wall temperature obviously. When the barrel wall thickness is large, the effect of cooling depends on the total cooling time and the longer heat dissipation time the greater the amount of heat dissipation. Because of the high frequency of rapid-fire and continuous shooting of weapons, the cooling time is very short, which limits the capacity of the cooling system. Therefore, to rapid-fire weapon barrel with water cooling, from the point of reducing the wall temperature, it should adopt cooling solutions in the small wall thickness and big flow velocity at the premise to meet the structural strength.

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