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Thermal Study of 155 mm Gun Barrel: A Review

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ABSTRACT

Thermal analysis of 155 Gun barrel is an important aspect of designing the gun barrel and deciding the maximum firing rate. The performance of any artillery depends upon the thermal behaviour of the gun barrel among various factors, and its availability for continuous firing depends on the maximum bore temperature and cook-off time of the barrel. In this paper, the effect of maximum bore temperature, cook-off**,** active cooling is reviewed. Heat transfer to the gun barrel surface is calculated using analytical analysis with given ammunition parameters. Analytical and finite element analysis of maximum bore temperature and cook-off time is also included. Finite element analysis of external Jacket water cooling of the barrel shows that the gun can fire continuously at three rounds per minute without reaching cook-off temperature.

Keywords: Cook-off; Barrel; Bore temperature; Firing

1. INTRODUCTION

The present study is focused on finding the cook-off time of 155 mm gun barrel using analytical analysis and finite element analysis using Ansys 17.2 at a particular rate of fire. Finite element analysis is also done to study the increase in cook-off time with external jacket water cooling.

The barrel is an integral part of any artillery gun system, which provides a closed chamber for propellant burning. In 155×45 mm gun barrel, pressure increases up to 420 MPa (maximum) with Bi-modular charge system (zone-6) having incremental charge, which leads to the achievement of a muzzle velocity of 920 m/s(maximum) within few milliseconds. Maximum bore surface temperature rises to about 1200 K within a few milliseconds and cools down in a few seconds. Firing from the gun can be continued only till the cook-off temperature of the propellant is reached. Once the Cook-off temperature is reached, the propellant will burn while loading in the gun chamber with some contact time and cause accidents. To avoid this situation, Cook-off analysis is done here to find the time to Cook-off. Maximum bore surface temperature is also calculated to study variation in the strength and properties of barrel material.

Gun barrel provides a chamber for propellant burning and close containment to build up pressure to give muzzle velocity to shell. The rifled barrel gives rotation to the shell. When the gun is fired, the inner surface of the gun barrel experiences high temperature and pressure. When the shell starts moving in the barrel, it exerts pressure on the inner surface of the barrel and causes barrel wear. As more rounds are fired from the gun, barrel wear increases, affecting the accuracy of fire, maximum pressure, and muzzle velocity and reduces the barrel life. Heat plays a major role in damaging the gun barrel[1].

Conditioning temperature of propellants affects the rate of burning of propellant, barrel wall temperature, maximum pressure and stresses in the barrel[2]. As the temperature of the propellant increases, maximum pressure and temperature of propellant gasses also increase. In case of 7.62 mm barrel with standard 7.62 mm NATO ammunition, it was observed maximum pressure changes from 306 MPa to 367 MPa for propellant temperature variation from -54 °C to +52 °C and maximum propellant gas temperature in barrel changed from 2478 K to 2974 K.

1.1 Bore Temperature and Cook-off

An experimental study of the effect of contact time and temperature on starting cook-off using 7.62 mm cartridge cases filled with double base propellant was done[3]. The rate of heat generated from propellant burning in the barrel chamber follows an exponential curve. The heat transfer from the gun barrel is a linear function. Cook-off of the gun barrel occurs after firing few rounds as the rate of heat produced from the propellant burning in the barrel chamber is more than the heat transfer from the gun barrel. This causes the accumulation of heat in the barrel material and a continuous rise in barrel bore surface temperature. It was observed that the cook-off temperature of the double-base propellant (with barrel used in the experiment) was between 151.4 °C to 153.4 °C within a contact time of 300 s[3].

It was found that exponentially decaying heat flux can be used to simulate the gun barrel temperature plot.[4]

A study of heat transfer to gun barrel for given ammunition parameters for 120 mm tank barrel using finite element method (FEM) is done[5]. The cook-off temperature of the propellant

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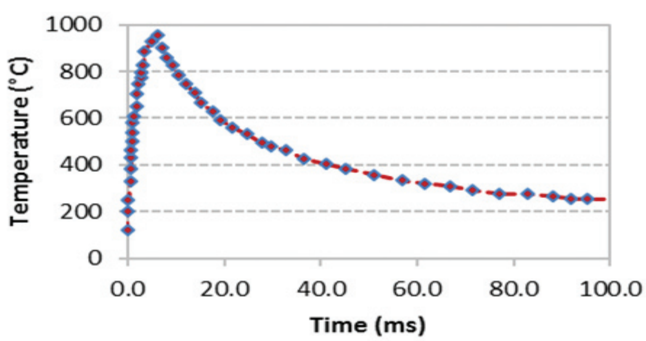
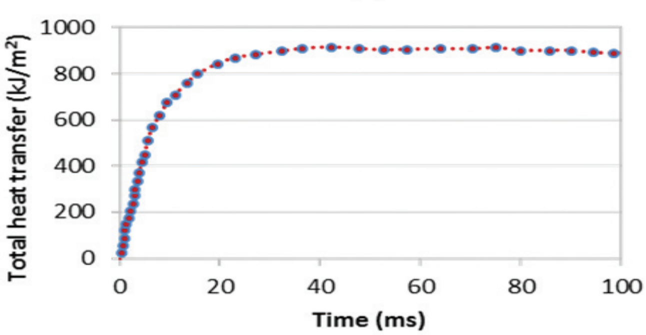
was assumed to be 180 °C. It was concluded that in the case of 6 rounds per minute firing rate, cook-off time was 507s. Hence, a 120 mm tank gun under consideration can fire 50 rounds continuously at a rate of 6 rounds per minute before reaching cook-off conditions[5].

Experimental work has been done to determine the temperature and heat transfer at the bore surface of the barrel at the start of rifling[6]. Two different propellants, one without any wear-reducing additive and the other with wear-reducing additive, were used in firing with a new barrel for each. Each propellant attained a maximum pressure of about 350 MPa and a muzzle velocity of about 940 m/s. Gun firing took place in two sets of conditions. In the first firing module, the barrel was at ambient temperature, and in the second firing module, the barrel was heated to 120 °C before firing. Results are shown in graphs[6]. Figure 1 shows the temperature-time curve and heat transfer-time curve at the start of rifling in the barrel. Figure 2 shows the maximum bore temperature for propellant *N* and *M* fired in un-heated barrels and the maximum bore temperature for barrels heated to about 120 °C[6].

From Figure 1(a), this is clear that during firing from a 155 Gun barrel, the maximum temperature at the inside bore surface of the barrel reaches about 950 °C in a short time of 5 ms. Bore surface temperature reaches about 250 °C in 100 ms, and further cooling occurs by natural convection. Figure 1(b) shows that the total heat transfer reaches 900 kJ/m^2 in 40 ms. This indicates that heat transfer reaches maximum once the shell has left the muzzle of the barrel (15 ms).



(a)

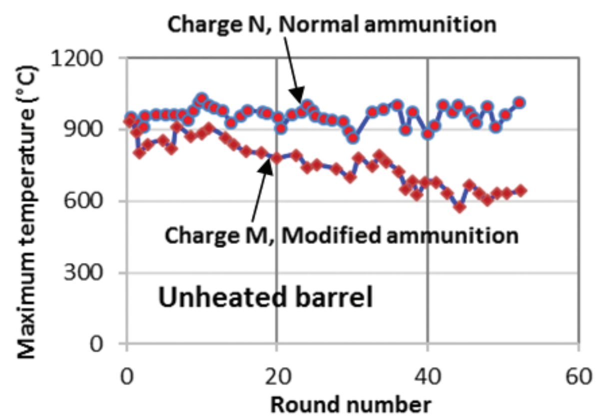


(b)

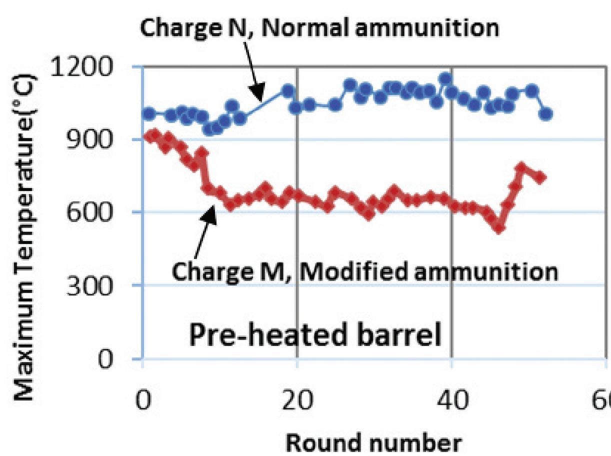
Figure 1. (a) Temperature-time curve, and (b) Heat transfer-time curve[6].

Figure 2(a) shows that the maximum bore surface temperature reduces from 900°C to 600°C after firing 40 rounds while using modified ammunition with wear-reducing additives. Initially, the barrel was at ambient temperature. As firing starts, it takes some time for additives to stick to the bore surface and reduces heat transfer to the barrel surface after firing a good number of rounds.

Figure 2(b) shows that if the pre-heated barrel is used for firing, the effect of wear-reducing additives starts appearing after firing ten rounds only as the wear-reducing additive layer forms earlier due to high temperature. The maximum bore surface temperature reduces from 900°C to 600°C after firing ten rounds while using modified ammunition with wear-reducing additives in the pre-heated barrel.



(a)



(b)

Figure 2. (a) Maximum bore temperature for propellant *N*, and *M* fired in un-heated barrel and (b) Maximum bore temperature for barrels heated to about 120°C[6].

Wear reducing additives do not have an instantaneous effect but increases after each firing. Additives can be mixed in the propellant to increase the life of the barrel. When the propellant burns in the barrel chamber, additive sticks to the barrel bore surface and reduces the heat transfer from the propellant gasses to the barrel surface. This reduces the barrel bore surface temperature. The higher temperature at the bore surface causes thermal stresses in the gun barrel. Also, high temperature at the bore surface can cause cracks in the bore surface and reduce the barrel life.

Transient heat transfer in a 155 mm gun barrel has been investigated numerically[7]. Heat transfer in the gun barrel can be solved by considering convection from the propellant gases and conduction in the radial direction in the cylinder wall. In this simulation, a time interval of 10 seconds is set for each gunshot, with a rest time of six seconds in every six gunshots. The initial temperature of the bore surface is 35.45 °C, while after the 27th of shooting, the initial temperature reaches 180 °C, which is the cook-off temperature. Gun barrel bore surface temperature increases after each firing. The gun barrel can shoot 27 times before it reaches the cook-off temperature with a total time of 294 seconds[7].

1.2 Barrel Cooling

Additives can be used in propellant to minimise the heat transfer to the gun barrel bore surface. Reduction of heat transfer to the gun bore surface due to additives can be attributed to a low-temperature gas layer formed next to the bore surface or to the reduction of turbulence in the boundary layer or to the absorption of heat by additive or to a low conductivity coating of additive[8]. Initially, titanium dioxide particles in paraffin wax were used as the first additives for propellant. When the propellant burns in the chamber, the titanium dioxide particles got stick to the bore surface and insulate the bore surface from high-temperature propellant gasses. In the case of propellant with additives, the maximum bore temperature reduced from 950° C to 600 °C in an unheated barrel and heat transfer per round reduced from about 950 kJ/ m^2 to about 600 kJ/ m^2. Generally, it takes more than 12 hours to cool down the barrel once the cook-off temperature is reached[9].

Barrel cooling is broadly classified as passive cooling and active cooling. Passive cooling technologies such as chromium/Tantalum coating and additives decrease the heat transfer from hot propellant gases to the bore surface of the gun barrel by acting as a thermal barrier. Active cooling consists of finned barrel cooling, forced air/liquid cooling and increase heat dissipation rate. Barrel cooling technology is widely used in Naval guns as they are mounted on warships, and weight is not a major factor as high rates of fire are the priority. Silicon dioxide, as an additive, can reduce the steel temperature by 150 °C[10].

Barrel liquid cooling can be done by internal cooling, mid-wall cooling and external cooling. Internal cooling can be done only after projectile exit and may cause thermal stresses in the gun barrel. External cooling requires jacket and flow devices and can increase the weight penalty and size of the barrel. Mid wall cooing is used in electromagnetic rail gun, in which thermal conditions are extreme[11].

The active cooling capacity of the gun barrel can be increased by either increasing heat transfer coefficient (increasing coolant velocity, specific coolant selection) or increasing heat transfer area by making fins (successful only in thin-walled barrels like in machine guns, mortars).

Active cooling methods are more efficient than passive cooling methods to avoid any chances of cook-off. However, external power source to circulate the coolant and coolant jackets increase the weight penalty**.** For active cooling with the liquid flow with heat transfer coefficient 20 kW/m^2-k in 120 mm tank barrel, the gun can fire six shells per minute continuously without cook-off[12].

Graphite foam has unique characteristics of large surface area, light in weight, high thermal conductivity. The machine gun has to fire thousands of rounds continuously and require a good heat sink for better performance. Machine gun barrel can be wrapped with a 6 mm graphite foam layer along with a 0.8 mm micro-jacket to take away all heat and convert the water in the jacket to superheated steam[13].

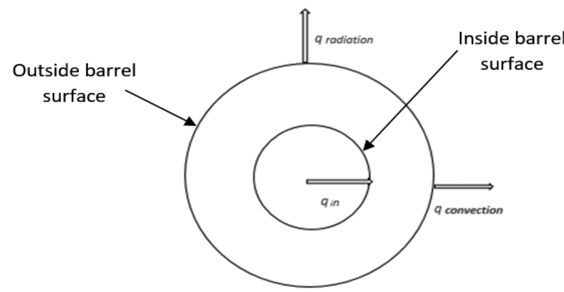


Figure 3. Smoothbore barrel cross-section.

Gasses temperature is assumed to be decaying exponentially, similar to the rate of decay of pressure in the gun barrel[14].

In the case of firing in an artillery gun, it is observed that ambient temperature also plays an important role in deciding the maximum number of rounds fired before reaching the self-ignition temperature of the propellant[15]. Ambient temperatures may vary from -40 °C in Siachin to 50 °C in Jaisalmer. If the ambient temperature is high, less heat will be transferred from

Table1. Dimensions and properties of barrel, charge and shot

Parameter	Notation	Value
Thermal diffusivity	K'	9×10^{-6} m^2/s
Thermal conductivity	K	35 W/m-k
Specific heat	C	490 J/kg-K
Density of steel	P	7860 kg/m^3
Mass of shot	m_r	40 kg
Muzzle velocity	V_m	886 m/s
Heat transfer coefficient at the outer surface of the barrel	h_∞	6.5 W/m^2-K
Maximum bore pressure	P_{max}	400 MPa
Flame temperature of the propellant	T_f	3000 K
Inner diameter of the bore	D	0.155 m
Inner surface area of the bore	$A_i=\pi dL$	9.734×10^{-4} m^2
Outer diameter of the bore	D	0.310 m
Outer surface area of the bore	$A_O=\pi DL$	1.947×10^{-3} m^2
Mass of propellant	m_c	16 kg
Cook-off temperature	T_C	453 K
Initial temperature	T_i	298 K

the outer surface of the barrel to the surroundings. This will cause an accumulation of heat in the barrel wall, and the gun can fire fewer rounds.

Gun tubes were used to be coated with Tantalum (Ta), Tungsten (W), Cobalt (Co), Chromium (Cr), Molybdenum (Mo) and Stellite during the second world war era. In the 1980s, use of a mixture of Talc, waxes and TiO_2 additives started. In the 1990s, electro-deposited chromium and nitride barrels were used[16]. Coatings mitigate erosion as they are not reactive to propellant product gases and reduce the peak temperature of barrel bore surface by insulating the thermal load to the gun base material. Coatings also reduce barrel wear caused by rubbing of the projectile with the barrel. Coating material must have good adhesion and the same coefficient of thermal expansion as gun barrel material to avoid thermal stress cracking.

2. ANALYTICAL ANALYSIS

2.1 Heat Transfer Analysis

Heat flux at the bore surface of a gun depends on the propellant gas density, velocity and temperature, and the temperature of the bore surface and the thermal properties of the gun steel. Heat conduction in the axial direction is assumed to be negligible compared to conduction in the radial direction. The heat produced due to friction between the driving band of the shell and bore surface is also neglected. Figure 3 shows the cross-section of the barrel with heat transfer at inner and outer surfaces.

The governing equation is the 1-D diffusion equation in a cylindrical coordinate system (conduction equation).

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{1}{K'}\frac{\partial T}{\partial t}$$

2.2 Maximum Bore Temperature

The present analytical study is based upon the Book "Transient temperature in engineering and science" by Dr B. Lawton and G. Klingenberg, page 453[17]. Table 1 shows the properties of charge, shot and barrel material along with the dimensions of the barrel.

A simple, explicit equation for maximum rise in bore temperature at the commencement of rifling may be approximated as:

$$\frac{T_f-1.8T_i}{T_{\max}-T_i}=1.8+\frac{288k}{R_e^{0.86}K_g}\sqrt{\frac{K_g}{k'}} \tag{1}$$

where $R_e = \frac{\rho v_m d}{\mu} = \frac{m_c v_m}{d^2\mu}$, $K_g = V_m{*}d$ and $K' = \frac{k}{\rho C_v}$

substituting in equation 1, we get

$$T_{max} = T_i+\frac{T_f-1\cdot 8Ti}{1\cdot 8+\dfrac{7130d^{2\cdot 22}}{m_c^{0.86}V_m^{0.36}}}$$

Using the values from Table 1, we get $T_{max} = 1207.1\ K$

2.3 Heat Input Per Round

When the shell is fired from the barrel, heat flux increase rapidly to the maximum value and then reduces slowly, so heat transfer modelling can be simplified by assuming heat flux as an exponentially decaying parameter. Based on this assumption, the following relation between heat transfer per round and maximum bore temperature is established[17].

$$q = q_0\, exp\left(-\frac{t}{t_0}\right) \tag{2}$$

where t_0 and q_0 are constants.

Total heat input is calculated by integrating equation (2) from time $t = 0$ to time t.

$$H = \int_0^t q\,dt = q_0\times t_0\times\left(1-e^{\frac{-t}{t_0}}\right) \tag{3}$$

Quantity $q_0 t_0$ is the total heat input at $t-\infty$, so equation (3) can be written as:

$$\frac{H}{H\infty}=1-exp\left(-\frac{t}{t_0}\right) \tag{4}$$

Figure 4 shows the plot of heat transfer for a solid subjected to exponentially decaying heat flux.

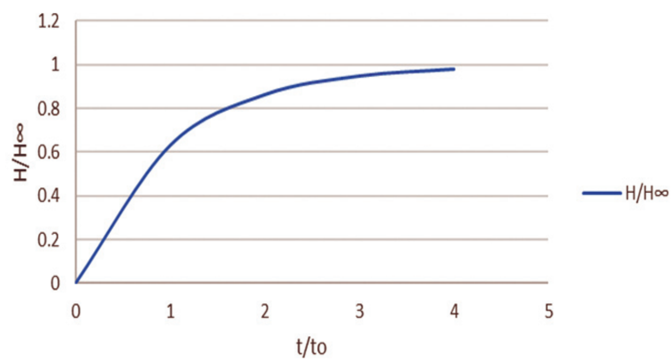


Figure 4. Heat transfer for a solid subjected to exponentially decaying heat flux.

Using Fourier's law and taking the Laplace transform of equation (4), and further applying the convolution theorem, we get

$$T\text{-}T_i = \int_0^t \frac{H_\infty}{kt_0}\sqrt{\frac{k'}{\pi t'}}exp\left(\frac{t'-t}{t_0}-\frac{x^2}{4.K'.t}\right)dt' \tag{5}$$

where t' is the variable of integration.

This is the general solution, but the integral is not standard, and so, in general, a numerical solution will have to suffice. However, a useful series solution can be found for the surface temperature. The useful solution can be found by making the above equation non-dimensional by writing:

$$K' = \frac{K}{\rho C},\ u = \frac{t}{t_0},\ \text{and } u' = \frac{t'}{t_0},\ x=0.$$

$$\frac{\sqrt{\pi k\rho_C t_0}}{H_\infty}(T_0-T_i)=\exp(-u)\int_0^u\frac{1}{\sqrt{u'}}\exp(u')du'$$

This does not have a standard solution, but it can be expressed as an infinite series by substituting the exponential series and integrating each term to give-

$$\frac{\sqrt{\pi k \rho_C t_0}}{H_\infty}\left(T_0 - T_i\right) = 2\sqrt{u}\exp\left(-u\right)\left(1 + \frac{u}{3} + \frac{u^2}{5*2!} + \ldots\right) =$$

$$2\sqrt{u}\exp\left(-u\right)\sum_{n=0}^{\infty}\frac{u^n}{\left(2n+1\right)n!}$$

This series converge rapidly for all values of u. The surface temperature reaches a maximum value at u=0.85, and the maximum surface temperature is given by-

$$T_{max} - T_i = \frac{1.082\, H\infty}{\sqrt{\pi k \rho C t_0}} \tag{6}$$

The time constant has been found to correlate with the maximum pressure, the projectile mass, the muzzle velocity, and the bore and can be estimated from

$$t_0 = 0.8\frac{m_r v_m}{d^2 P_{max}} \tag{7}$$

Value of heat transfer per round is given by:

$$H_\infty = \frac{K}{1.082} * \left(T_{max} - T_i\right) * \sqrt{\frac{\pi * t_0}{K'}} \tag{8}$$

Using the values from Table 1, we get $t_0 = 2.950*10^{-3}$

Heat input per round $H_\infty = 943465.81$ J/ m^2

2.4 Cook-off Analysis

The cook-off temperature of the propellant is assumed to be 180 °C. To find cook-off time, the following assumptions are made[12]-

1- Constant heat input at bore surface (constant fire rate).

2- Only convection at the outer surface.

3- Constant barrel temperature across the barrel wall

Energy balance for gun barrel is,

$mC\,(dT/dt) = H A_i R_f - h_\infty A_0 (T - T_\infty)$ (9)

where $m = \rho\,(\pi/4)\,(D^2 - d^2) * L,\ A_i = \pi\, d\, L,\ A_0 = \pi\, DL$

Let $\theta = T - T_\infty$ = Temperature above the ambient temperature

$$\frac{d\theta}{dt} = \frac{dT}{dt}$$

From eqn. (9) $mC\,\dfrac{d\theta}{dt} = H A_i R_f - h_\infty A_0\, \theta$

$$\frac{d\theta}{dt} = \frac{HA_iR_f}{mC} - \left(\theta / \frac{mC}{h_\infty A_0}\right)$$

Let $t_0 = \dfrac{mC}{h_\infty A_0}$ = time constant, measures how fast barrel temperature responds to heat flow.

$$\frac{d\theta}{dt} + \frac{\theta}{t_0} = \frac{\theta_\infty}{t_0} \tag{10}$$

$\theta_\infty = \dfrac{HA_iR_f}{h_\infty A_0}$ = finite temperature rise if firing continues for infinite time

Solution of eqn. (10) with θ = 0 at t = 0 is given by-

$$\frac{\theta}{\theta_\infty} = 1 - \exp\left(-\frac{t}{t_0}\right) \tag{11}$$

Let t_c = cook–off time for barrel, T_c = cook-off temperature of barrel

then $\theta = \theta_c,\ 1 - \dfrac{\theta_C}{\theta_\infty} = \exp\left(\dfrac{-t_c}{t_0}\right),\ \dfrac{t_c}{t_0} = -\ln\left(1 - \dfrac{\theta_c}{\theta_\infty}\right)$ (12)

Assuming thermal properties of gun barrel remain constant at elevated temperatures. Consider a bore element of 2 mm at the chamber portion of the barrel for simple analysis. Heat input per round is 943465.81 J/ m^2.

When firing rate is 4 rounds/minute.

$m = \rho_{\frac{\pi}{4}}\left(D^2 - d^2\right)L$ = 7860*0.785*(0.310^2 -0.155^2) * 2*10^{-3} = 0.889 kg

$t_0 = \dfrac{mC}{h_\infty A_0}$ = (0.889*490)/(6.5*1.947*10^{-3}) = 34420.60

$\theta_\infty = \dfrac{HA_iR_f}{h_\infty A_0}$ = (943465.81*9.734*10^{-4}*4)/ (6.5*1.947*10^{-3}*60) =4837.79

$\theta_c = T_c - T_\infty = 180 - 25 = 155^\circ$ C

$\dfrac{t_c}{t_0} = -\ln\left(1 - \dfrac{\theta_c}{\theta_\infty}\right)$ We get t_c = 1120.87 sec.

The gun can fire continuously for 18 minutes at the rate of 4 rounds per minute.

Table 2. Data input for numerical modelling for peak barrel inside surface temperature

Parameter	Value
Length of barrel cross-section	2 mm
Convection at outside surface (h)	6.5 W/m^2-K
Emissivity coefficient for radiation heat transfer at outside surface (e)	0.75
T_∞	298 K
Analysis run time	20 ms
Initial time step	0.00001 s
Minimum time step	0.00001 s
Number of elements	106630

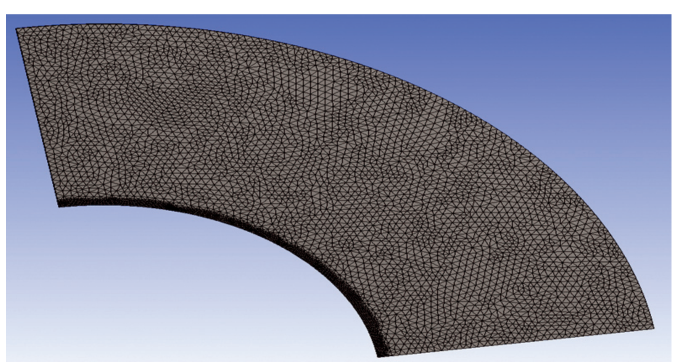


Figure 5. Fine meshed model of a quarter section of the barrel for peak temperature.

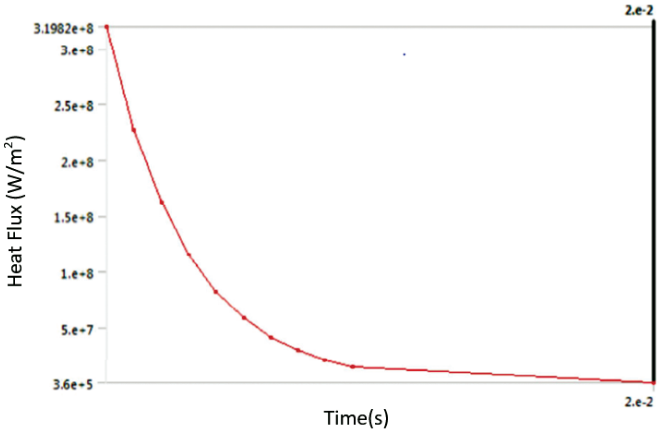


Figure 6. Exponentially decaying heat flux input profile at the inside surface of gun barrel.

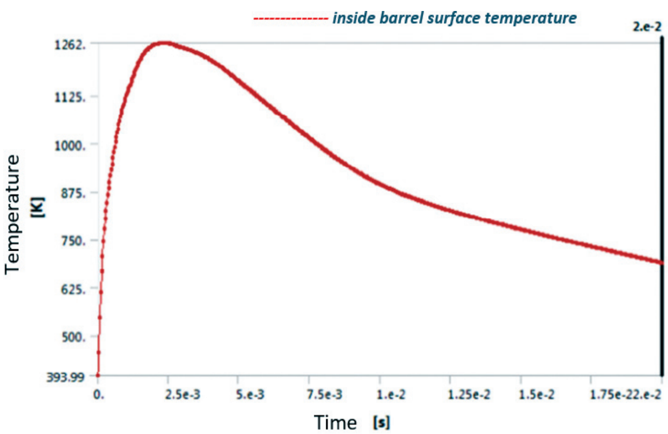


Figure 7. Temperature variation at the inside surface of barrel with input exponential heat flux.

3. NUMERICAL MODELLING

3.1 Numerical Modelling for Maximum Bore Temperature

Quarter section of gun barrel cross-section is taken to reduce the number of elements and calculation time. Two faces along the length of the barrel are insulated to neglect axial heat transfer. Software used for modelling- Ansys 17.2, Transient thermal module. Exponential decaying heat flux can be calculated as follows.

$$q = q_0 \, exp.\left(-\frac{t}{t_0}\right) \tag{13}$$

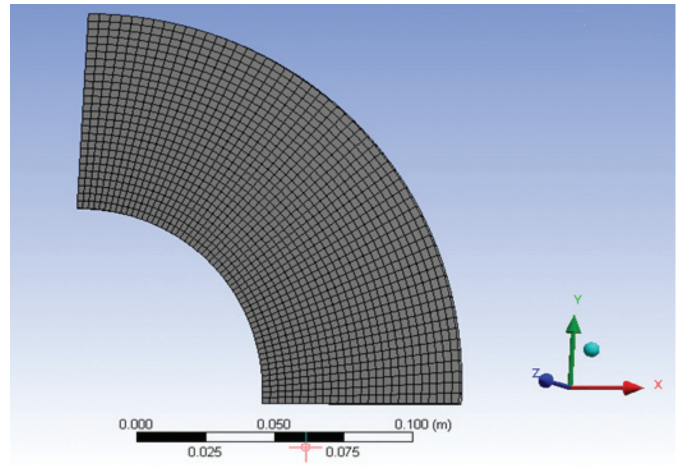


Figure 8. Meshed model of a quarter section of the barrel.

Table 3. Data input for numerical modelling with radiation and convection

Parameter	Value
Length of barrel cross-section	2 mm
Convection at outside surface (h)	6.5 W/m^2–K
Emissivity coefficient for radiation heat transfer at outside surface (e)	0.75
Free stream temperature (T_∞)	298 K
Analysis run time	1200 s
Initial time step	0.01 s

Total heat input is then calculated by integrating the above equation from time t= 0 to time t.

$$H = \int_0^t q dt = q_0 * t_0 * \left(1\text{-}e^{\frac{-t}{t_0}}\right) \quad H_\infty = q_0 * t_0 \text{ quantity } q_0 t_0$$

is the total heat input at $t - \infty$, so Eqn (13) can be written as

$$q = \frac{H_\infty}{t_0} \exp\left(-\frac{t}{t_0}\right)$$

Here $t_0 = 2.950*10^{-3}$ $H_\infty = 943465.81$ J/m^2, $q = 319.82 * 10^6 \exp.(-t/2.95*10^{-3})$

This is the exponential decaying heat flux input to find the peak temperature on the inside surface of the gun barrel.

Table 2 shows the Data input for numerical modelling for peak barrel inside surface temperature. Figure 5 shows the fine Meshed model of a quarter section of the barrel for peak temperature analysis. Figure 6 shows the exponentially

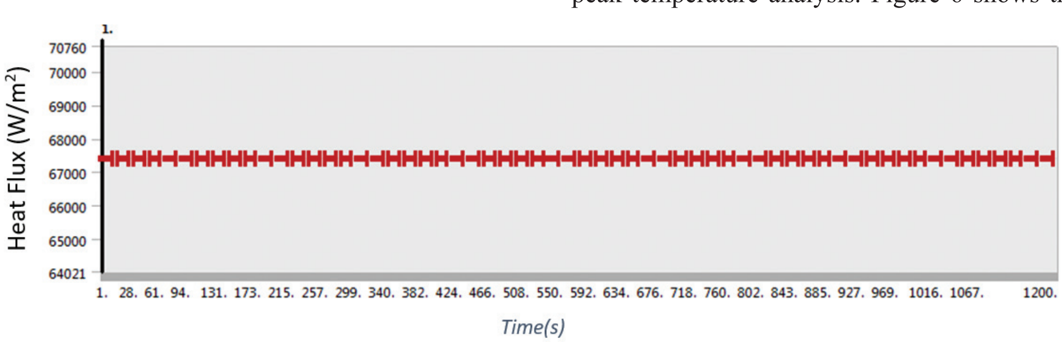


Figure 9. Heat flux input profile at the inside surface of gun barrel.

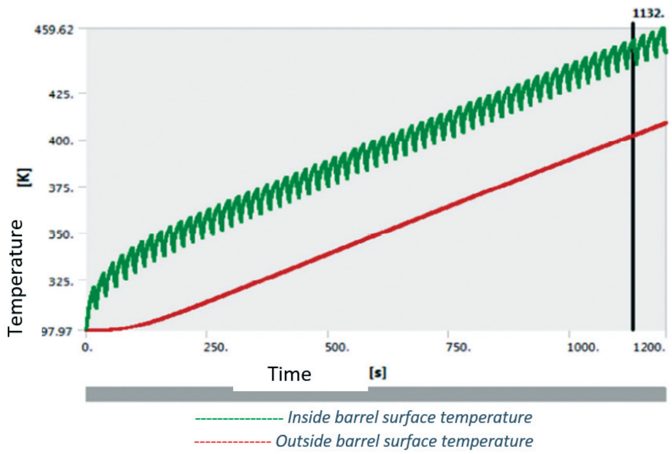


Figure 10. Temperature variation at inside and outside surface of barrel with time.

decaying heat flux input profile at the inside surface of the gun barrel. Figure 7 shows the temperature variation at the inside surface of the barrel with time with exponential heat flux.

As per numerical simulation, the maximum temperature reached at the inside surface of the gun barrel is 1262 K. Time at which the maximum temperature reached is 2.5 ms.

3.2 Numerical Modelling Considering both Convection and Radiation

Heat transfer in the gun barrel is considered as quasi-steady heat transfer in which heat input per round is treated not as a series of impulses but a continuous, quasi-steady heat input. This gives accurate predictions of barrel temperature at the moment before a round is fired and saves time in analysis.

Table 4. Input data for numerical modelling with convection only

Parameter	Value
Length of barrel cross-section	2 mm
Convection at outside surface (h)	6.5 W/m^2-K
Free stream temperature (T_∞)	298 K
Analysis run time	900 s
Initial time step	0.01 s

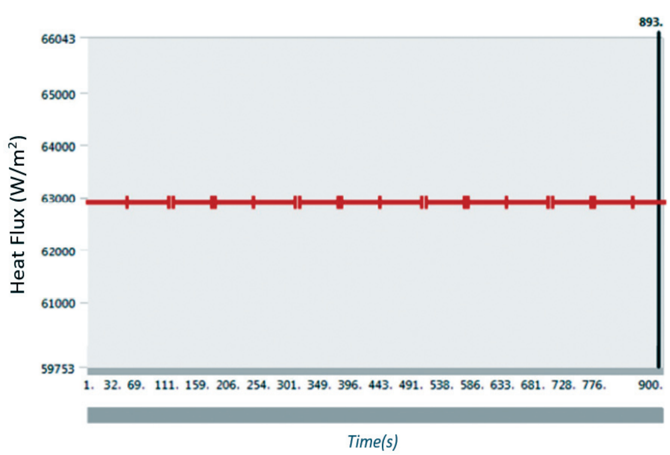


Figure 11. Heat flux input profile at the inside surface of gun barrel for case 3.3.

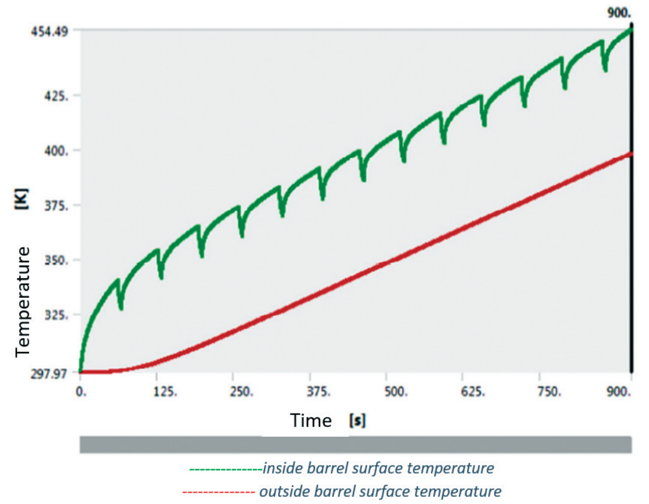


Figure 12. Temperature variation at the inside and outside surface of barrel with time for case 3.3.

This is an excellent method for predicting cook-off temperature (Page 456)[17]. However, this method is not very accurate in computing the maximum bore temperature while the projectile is in the barrel.

The firing rate is three rounds per minute. Quarter section of gun barrel cross-section is taken to reduce the number of elements and calculation time. Two faces along the length of the barrel are insulated to model the negligible axial heat transfer. Software used for modelling- ANSYS 17.2, Transient thermal module. Table 3 shows the data input for numerical modelling with both radiation and convection at the outside surface. Figure 8 shows the meshed model of a quarter section of the barrel.

A gap of 6 seconds is taken after firing each round to open the breech block and load the next round. So heat flux input is given in a cycle ON for 14 seconds and OFF for 6 seconds for firing 3 rounds per minute (14+6+14+6+14+6 cycle every minute). Heat flux for firing rate of 3 round per minute Q = (H_∞ * R)/t

$$Q = (943465.81*3)/60 = 47173.29 \text{ W/m}^2$$

For cyclic flux, as mentioned above, Flux will be high to give the same heat input as given by three rounds per minute. Figure 9 shows the heat flux (W/m^2) input profile at the inside surface of the gun barrel. Figure 10 shows the temperature variation at the inside and outside surface of the barrel with time after solving the numerical model.

$$Q' = (47173.29*60) / (3*14) = 67390.41 \text{ W/m}^2$$

Table 5. Properties of water used as the coolant

Parameter	Notation	Value
Density	ρ_w	997 kg/m^3
Prandtl number	P_r	5.83
Conductivity of water	K_w	0.613 W/m-k
Dynamic viscosity of water	μ_w	855 ×10^{-6} Ns/m^2
Internal diameter of water jacket	D_1	310 mm
External diameter of water jacket	D_2	320 mm
Velocity of water flow	V_w	0.25 m/s

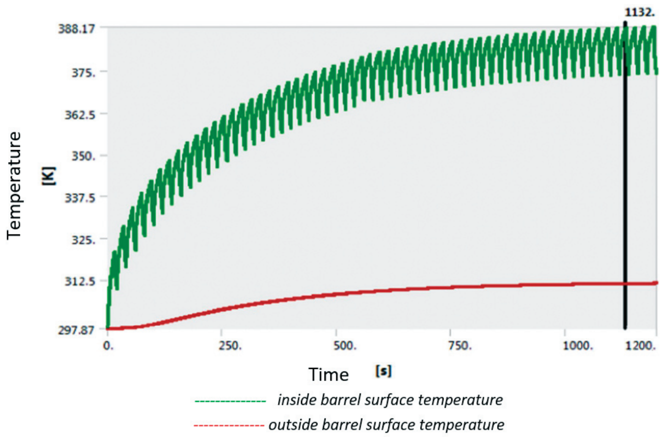


Figure 13. Temperature variation at the inside and the outside surface of barrel with time.

In Numerical modelling, if the element size is 3 mm, number of elements after meshing are 1456, and if the element size is 2 mm, the number of elements is 3276. However, on solving both cases in ANSYS 17.2, the results are similar to, as mentioned in Fig. 10. It shows that the results obtained are independent of mesh size/element size.

3.3 Numerical Modelling with Convection

The firing rate is four rounds per minute. Table 4 shows the input data for Numerical modelling with only convection at the outside surface of the gun barrel.

Heat flux for firing rate of 4 round per minute

$Q = (H_\infty * R)/t$

Table 6. Cook-off time data comparison with published results

Cook-off time published in the paper (s)	Cook-off time by finite element method (s)	Difference (%)
1060	1132	6.79%

$Q = (943465.81*4)/60 = 62897.72$ W/m^2

Continuous heat flux is applied with a cycle of 60 seconds ON and 6 seconds OFF for firing 4 rounds per minute. Average heat flux is calculated from total heat transfer from 4 rounds distributed over 1 minute. Figure 11 shows the heat flux (W/m^2) input profile at the inside surface of the gun barrel. Figure 12 shows the temperature variation at the inside and outside surface of the barrel with time.

3.4 External Liquid Cooling of Barrel

Water is used as the coolant. Table 5 shows the properties of water used as the coolant.

Calculation of heat transfer coefficient for water as cooling medium-

Hydraulic Diameter $d_e = 4[\pi/4*(D_1^2 - D_2^2)]/\{\pi (D_1+D_2)\}$

$d_e = D_1 - D_2 = 320 - 310$

Table 7. Cook-off time data comparison with analytical results

Cook-off time by analytical method (s)	Cook-off time by finite element method (s)	Difference (%)
1120.87	893	20.32%

$d_e = 10$ mm

$R_e = (\rho_w * V_w * d_e)/\mu_w = (997*0.25*0.01)/(855*10^{-6})$

$R_e = 2915.2$

Since Reynolds number is more than 2300, this is a Turbulent flow.

Using Dittus- Boelter Equation

$N_u = 0.023\, R_e^{0.8}\, P_r^{0.4} = h\, d_e / K_w$

$h = 0.023\, R_e^{0.8}\, P_r^{0.4} * (K_w/d_e)$

$h = 1687.3$ W/m^{2}K

Mass flow rate of water, $m_w = \rho\, A\, V_w = 1.23$ Kg/s

Heat flux for firing rate of 3 round per minute

$Q = (H_\infty * R)/t$

$Q = (943465.81*3)/60 = 47173.29$ W/m^2

Heat flux input is given in a cycle ON for 14 seconds and OFF for 6 seconds for firing three rounds per minute. (14+6+14+6+14+6 cycle every minute).

$Q' = (47173.29*60) / (3*14) = 67390.41$ W/m^2

Figure 13 shows the temperature variation at the inside and the outside surface of the barrel with time with external liquid cooling.

4. RESULTS AND DISCUSSION

4.1 Cook-off Time Validation with Published Results

Results for case 3.2 of numerical modelling are compared with results of the experimental firing of 155 mm gun barrel from research paper "Temperature and heat transfer at the commencement of rifling of a 155 mm gun" by Dr B Lawton Cranfield University, UK (2001)[6]. As per data available in the research paper, cook-off took place after firing 53 rounds at three rounds per minute which gives cook-off time as 1060 s. Table 6 shows the cook-off time data comparison with published results.

4.2 Cook-off Time Validation with Analytical Results

The results of case 3.3 of numerical modelling considering only convection are compared with the analytical analysis done with convection only. There is a significant difference in the value of cook-off time obtained from two methods, as the assumption of constant barrel temperature across the barrel wall in the analytical analysis does not hold correct for a high firing rate. Difference in two methods may have occurred as 3D model of gun barrel chamber is used in numerical modelling in Ansys. Due to 3D model, the assumption of one dimensional axisymmetric case does not hold true and some heat transfer may have occurred in longitudinal direction. Table 7 shows the cook-off time data comparison with analytical results.

4.3 Maximum Temperature Results at Barrel Inside Surface

The maximum temperature reached at the inside surface of the gun barrel as per numerical analysis is 1262 K. The maximum temperature reached at the inside surface of the gun barrel as per analytical analysis is 1207 K. The difference in maximum temperature by two methods is 4.35%. It takes only 2.5 ms to reach the maximum temperature at the barrel inside surface.

4.4 Cook-off Time with External Forced Liquid Cooling

From the temperature plot of the barrel inside surface temperature with forced liquid cooling, It is observed that the external water cooling of the barrel is an efficient way to increase the cook-off time. In the present case of firing three rounds per minute and external forced cooling with a water flow rate of 1.23 Kg/s, the cook-off is never reached. The gun can fire continuously at three rounds per minute as barrel inside surface temperature reaches up to 388 K only.

5. CONCLUSION

In this paper, analytical analysis of maximum bore temperature, heat input per round, and cook-off analysis of 155 mm gun barrel has been done to find the maximum time up to which the gun can fire safely. Cook-off time and maximum bore temperature have also been determined using Finite element analysis in ANSYS 17.2.

Numerical modelling of external liquid cooling of the barrel shows that this is an efficient method to increase the cook-off time, and the gun can fire continuously at three rounds per minute. Findings can be concluded as:

- Considering convection and radiation heat transfer at the outer surface of the barrel, the 155 mm artillery gun can fire 56 rounds at a rate of 3 rounds per minute as per numerical modelling in ANSYS 17.2. The gun will cook off after 1132 seconds.
- The gun can fire continuously at three rounds per minute as barrel inside surface temperature reaches up to 388 K only with forced water cooling of 1.23 Kg/s of flow at external barrel surface.

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