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COOK OFF STUDY OF A 120 MM GUN BARREL USING FINITE ELEMENT METHOD

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Abstract

Cook off study is very important to calculate firing rate of a gun. In this paper using analytical method heat transfer to the gun barrel for given ammunition parameters was calculated. Cook off study was done analytically and subsequently finite element method was employed for cook off study using ANSYS 14.0 software .the simulation was run for 521.9 seconds and the result was found to match satisfactorily to the corresponding analytical result. Proposed scheme can accurately study cook off of a gun barrel so accurate firing rate can be determine The cook-off temperature was assumed to 180 ^{0}C for the propellant[1]. The results presented in this report are related to service condition only at 20 ^{0}C.

Keywords: cook-off, gun barrel, wear, finite element method, firing rate.

1. Introduction

When there is firing from a gun, there is large amount of heat input to the bore surface of a gun barrel, and the heat transfer to the barrel is mainly due to forced convection from the hot gases generated inside the barrel due to combustion of propellant. Generally, after firing the barrel is naturally cooled by convection and radiation at its outer surface but natural cooling is inefficient and only a fraction of the total heat input is transferred to the external environment. Hence, during continuous firing at a high rate of fire, the temperature of the gun barrel keeps on rising to ultimately equal to the cook-off temperature. At cook-off temperature, the self ignition of propellant takes place. This premature self-ignition may result in serious damage to the gun barrel and injury to crew members.

Thus, for finding out the maximum firing rate cook-off study is of utmost significance. In this work, a scheme for cook off study of a gun barrel using FEM was proposed and accuracy of the scheme was checked with the analytical results. Present work includes barrel cook off study divided into two parts:

a. Determination of the total heat transfer during a gun fire from hot propellant gases to the gun bore surface
b. Cook off study of the barrel resulting from the heat transfer.

2. Formulation Of Gun Tube Heating Problem

Heat transfer to the gun bore surface can be approximated as an exponentially decaying heat flux [8], [6].

Figure 1 shows a schematic of the heat transfer in a gun barrel.

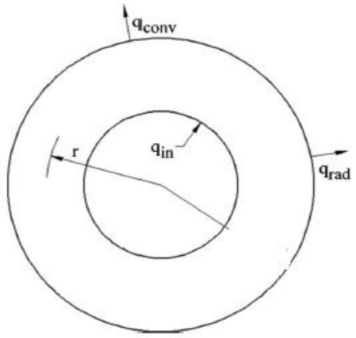

Fig.1. Schematic of heat transfer to gun barrel

Following assumptions and consideration have been made during the present study:

a. The heat conduction in the axial direction is negligible in comparison to conduction in the radial direction [2] and hence, ignored.
b. Friction heating between the projectile driving band and the bore surface was neglected [3].
c. Any effect of gravitation on convection heat transfer was also neglected.
d. The barrel was assumed to be uniformly thick at any transverse cross section along its length.
e. The mathematical formulation is presented using the cylindrical coordinate system.

Based on the above assumptions, any possibility of azimuthal variation of temperature was removed and the problem was reduced to a one-dimensional axisymmetric case. The governing equation, Eq. (1) is the diffusion equation, which is Fourier's conduction equation, combined with the energy equation in cylindrical coordinates [7]

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{1}{K}\frac{\partial t}{\partial t} \qquad (1)$$

Where, r is the radius of barrel at chamber, varying from R_i to $R_{0.}$ k and K is the thermal conductivity and thermal diffusitivity of gun steel, assuming constant thermo-physical properties. The initial uniform barrel temperature is taken as 293 K. The boundary conditions at the bore surface and the outside barrel surface are given by Eq. (2). and Eq. (3). respectively

$$-k\frac{\partial T}{\partial r}=h_g\left(T_g-T\right) \qquad (2)$$

$$-k\frac{\partial T}{\partial r}=h_\infty(T-T_\infty) \qquad (3)$$

Where, h_g is the combined convective heat transfer coefficient between the bore surface and hot propellant gases based on exponentially decaying heat flux, the following relation between heat transfer per round and maximum bore temperature has been derived in [4],

$$H_\infty = \frac{\kappa * (T_{max} - T_i)}{1.082} * \sqrt{\frac{\pi * t_0}{K}}$$

Where time constant t_0 is:

$$t_0 = \frac{0.8\,(m_r V_m)}{(d^2 P_{max})}$$

Table.1

The parameter used and heat input result

Notation	Parameters	Value
K	Thermal diffusivity	9 e -6 m^2/s
κ	Thermal conductivity of the barrel material	35 W/mK
m_r	Mass of the shot	6.8 kg
P_{max}	Maximum bore pressure	510 MPa
t_0	Time constant	0.00123 s
H_∞	Heat input per round	656833.6138J/m^2

For calculating the time for cook-off some simplifying assumptions [5], are taken into consideration the assumptions are: Constant heat input at the bore surface (constant fire rate). Only convection at the outer surface, barrel temperature is constant across the barrel wall thickness then by using energy balance for the gun barrel

$$mC_v \frac{dT}{dt} = HA_i R_f - h_\infty A_0 (T - T_0) \qquad (4)$$

Where

$$m = \rho \frac{\pi}{4}(D^2 - d^2)L \;, A_i = \pi dl \;, \quad A_0 = \pi DL$$

Eq. (4) shows that the higher will be the heat transfer coefficient, lower will be the steady state temperature of the barrel, and lower be the firing rate, lower be the steady state temperature of the barrel.

Let $\theta = T - T_\infty$

$= temperature\ above\ ambiant\ temperature$

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

Eq. (4) can be re written as:

$$\frac{d\theta}{dt}+\frac{\theta}{t_0}=\frac{\theta_\infty}{t_0} \qquad (5)$$

Where

$$t_0=\frac{m\,C_v}{h_\infty A_0}$$

t_0 is the time constant, and it measure of how fast barrel temperature responds to heat flow and

$$\theta_\infty=\frac{HA_iR_f}{h_\infty A_0}$$

θ_∞ is finite temperature rise if firing continued for an infinite time, the solution of Eq. (5) with initial condition

θ=0 at t=0 is:

$$\frac{\theta}{\theta_\infty}=1-\exp\left(\frac{-t}{t_\infty}\right) \qquad (6)$$

Let ' t_c' is the cook-off time for the barrel and 'T_c' be the cook off temperature of the barrel then $\theta = \theta_c$

This gives:

$$\frac{t_c}{t_o}=-\ln\left(1-\frac{\theta_c}{\theta_\infty}\right) \qquad (7)$$

The cook-off time was calculated analytically by using Eq. (7). Assuming the thermal properties of the barrel material remains constant, at the elevated temperature, and consider a bore element of .01 mm for the simplicity of analysis because heat input was per m^2 so there was no effect of barrel length on the result. The values of the parameters in above equation to calculate cook-off time are listed in table. 2.

Notation	**Parameter**	**Value**
T_c	Barrel cook-off temperature	180^0 C
A_i	Inner surface area of bore	.0075398 m^2
A_0	Outer surface of the bore	0.012566 m^2
H	Heat transfer per unit area per round	656833 j/m^2
D	Outer diameter of bore	0.2 m

D	Inner diameter of bore	0.120 m
h_∞	Heat transfer coefficient at outer surface of barrel	6.5 W/m^{2}K
C_v	Specific heat	490 j/kg K
L	Length of the bore barrel element	0.01mm
ρ	Density of barrel	7860 kg/m^3
t_0	Time constant	18960.73

Table. 2: Parameters used to calculate cook-off time

a. when firing rate is six rounds per minute:

$$t_0 = \frac{m\, c_v}{h_\infty A_0}$$

$$= \frac{7860 * \pi * (0.2^2 - 0.12^2) * 0.02}{6.5 * \pi * 0.2 * 0.02 * 4} = 18960.73$$

and $$\theta_\infty = \frac{H A_i R_f}{h_\infty A_0}$$

$$= \frac{656833 * \pi * 0.12 * 0.02 * 6}{6.5 * \pi * 0.2 * 0.02 * 60} = 6030.07$$

By putting the value of θ_∞ and t_0 in Eq. (7) we get t_c =507 s so barrel will cook-off after 507 s at a firing rate of six rounds per minute.

3. Finite Element Model Analysis

A one-dimensional, transient thermal analysis was performed with the FEA package ANSYS 14.0 to study cook off of a gun barrel. Chamber of only 0.01 mm length was modelled to avoid heat transfer in longitudinal direction and to reduce the calculation time. The length of the chamber will
not have any effect on the heat transfer and temperature variation along the radius as the heat input to the model in ANSYS is given as heat flux (W/m^2) at the inner surface of barrel and at outer surface of barrel convection was applied with a heat transfer coefficient of 6.5 W/m^{2}K other surface of barrel were perfectly insulated to prevent the heat transfer in axial direction.

The rate of fire for the given 120 mm gun is 6 rounds per min and the cycle may be repeated after 10 s , the heat flux per unit time for firing rate of six rounds per minute can be calculated as following,

$$Q = \frac{H_\infty * R_f}{t}$$

Where
'H_∞' is heat input per unit round per unit area in J/m^2.
'R_f' is rate of fire.

't' is duration of firing.

So

$$Q = \frac{656833.6138 * 6}{60} = 65683.36\ W/m^2$$

In the present study case this heat flux was applied for 60 s with a break of 6s, for 521.9 s. with a time step of 0.01 s and convergence was also checked at different time step and element size. This induces very acute temperature gradients near the bore surface; hence a very fine mesh was used in that zone. Figure. 2 shows meshed model of bore surface.

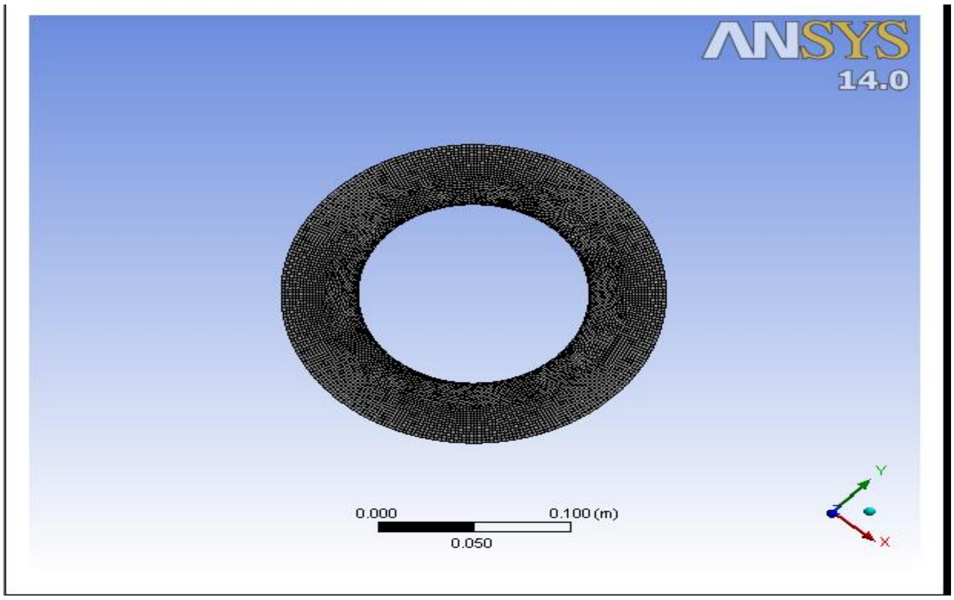

Fig. 2. Meshed model of bore surface

The bore temperature, after a number of cycles, and the corresponding time was noted down. The following table shows the heat input for analysis. Value of heat input is slightly more than the value calculated above, for sixty seconds because in software we cannot apply two values at same time e.g. maximum and zero value at same point sixty second so to compensate the decrease in heat input due to software limitation some extra value of heat input was applied as shown in table. 3.

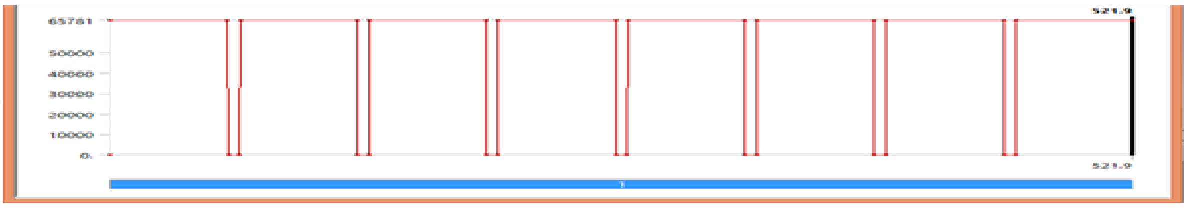

Table 3: Heat input applied for constant heat supply for sixty seconds for firing rate of six rounds per minute

4. Results And Discussion

when firing rate of six rounds per minute

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(a.) The cook-off temperature was 507 s when calculated analytically by using Eq. (7). Therefore, the bore temperature will not reach the cook-off temperature for 50 cycles i.e. gun can fire 50 rounds without reaching cook of limit at a time.

(b.) Finite Element Method results:

The cook-off temperature was reached in 476.8 s when heat was supplied continuously for sixty seconds with six seconds gap. Therefore, the bore temperature will not reach the cook-off temperature for 44 cycles i.e. gun can fire 44 rounds without reaching cook of limit. The variation of temperature with time is shown in the Fig. 3. Variation of temperature in radial direction is shown in Fig. 4.

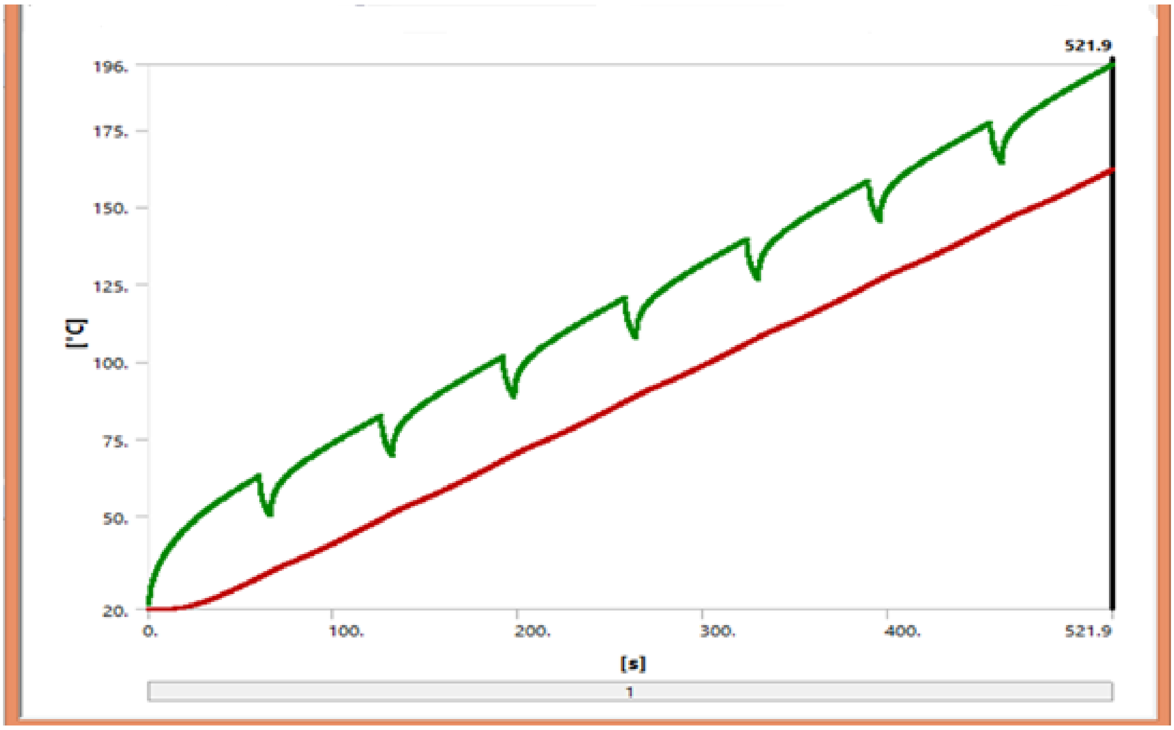

Figure. 3: Variation of temperature with time firing rate of six rounds per minute with constant heat supplied for sixty seconds

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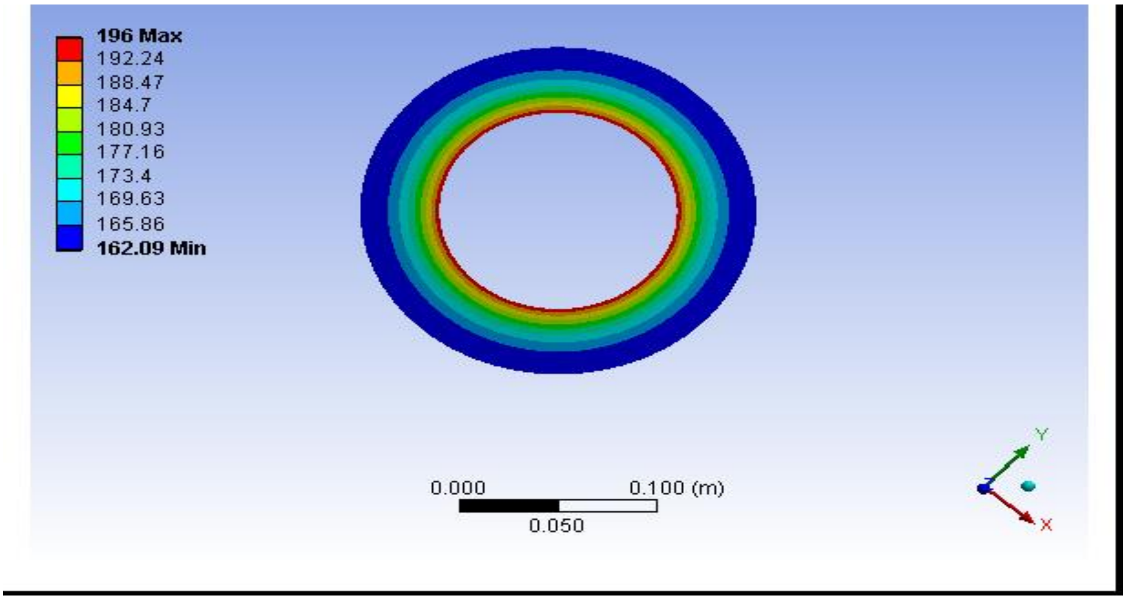

Figure. 4: Temperature variation in radial direction for a firing rate of six rounds per minute with constant heat supplied for sixty seconds

The percentage variation with finite element method is approximately 5.9 %. The difference in two methods may have occurred due to the 3D model used to represent the portion of barrel chamber. Due to the 3D model, the assumption of one-dimensional axisymmetric case was invalidated and there was some heat transfer in the longitudinal direction as well. However, it is the limitation of ANSYS that in 2D analysis, the heat flux in W/m^2 is not recognized by the software. Whereas, the results in the present study are in good agreement (only 5.9 % variation) and no further improvement was felt. However, the results may further be improved by reducing the length of the barrel modeled.

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5. Conclusion

Present scheme of cook off study of the gun barrel is analytical valid. with the help of Proposed scheme we can find no of shots fired before reaching the cook off of a gun barrel at a given firing rate. The small variation in the results was also discussed and remedy for further improvement in the results was suggested. In this direction, an important advantage is offered by proposed scheme, as it couples internal ballistic parameters with the inputs for finite element methods.

6. Acknowledgment

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7. Nomenclature

D	Bore diameter
h_∞	Heat transfer coefficient
H_∞	Heat input per round
κ	Thermal diffusivity
K	Thermal conductivity of the material
m_c	Mass of propellant
m_r	Mass of the shot
P_{max}	Maximum bore pressure
t_0	Time constant
T_f	Flame temperature of propellant
T_i	Initial temperature
V_m	Muzzle velocity
t	Duration of firing
R_f	Rate of fire
t_c'	Cook-off time for the barrel
T_c	Cook off temperature of the barrel
θ_∞	Finite temperature

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