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UNSTEADY THERMAL STUDIES OF GUN BARRELS DURING THE INTERIOR BALLISTIC CYCLE WITH NON-HOMOGENOUS GUN BARREL MATERIAL THERMAL CHARACTERISTICS

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Abstract: In this study, unsteady heat transfer problem has been solved to calculate the temperature distribution of a machine gun barrel. Time dependent convective heat transfer coefficient to predict the entire wall temperature of the barrel wall has been calculated by means of internal ballistic theory. The numerical solution of the differential equation was carried out by means of finite difference method. Thermal characteristics of the gun barrel material are considered to be temperature dependent. The study is extended also to cover the multi shot ballistic cycle, such that it would be possible to obtain the cook-off temperature of the gun. The numerical results are compared with the experimental results found in literature. The agreement between them is quite satisfactory.
Keywords: Heat transfer in gun barrels, interior ballistics, thermal characteristics of the gun barrel materials, convective heat transfer, cook-off temperature.

NAMLU MALZEMESİ ISIL KARAKTERİSTİKLERİ HOMOJEN OLMAYAN SİLAH NAMLULARININ İÇ BALİSTİK ÇEVRİM SIRASINDA ZAMANA BAĞLI ISIL İNCELENMESİ

Özet: Bu çalışmada bir makineli tüfek namlusunun sıcaklık dağılımını hesaplamak için zamana bağlı ısı transferi problemi çözülmüştür. Namlunun tüm et kalınlığı sıcaklığını tahmin etmek için zamana bağlı taşınımsal ısı transferi katsayısı iç balistik teorisi yardımıyla hesaplanmıştır. Diferansiyel denklemin nümerik çözümü sonlu farklar yöntemiyle yürütülmüştür. Tüfek namlu malzemesinin ısıl karakteristikleri sıcaklığa bağlı olarak dikkate alınmıştır. Çalışma, seri atışlı balistik çevrimi de kapsayacak biçimde genişletilmiş olup böylece tüfeğin kendi kendine ateşleme (cook-of) sıcaklığını hesaplamak mümkün olmaktadır. Nümerik sonuçlar literatürdeki deneysel sonuçlarla karşılaştırılmıştır. Her ikisi arasındaki uyum gayet tatminkardır.
Anahtar Kelimler: Silah namlularında ısı transferi, iç balistik, silah namlu malzemelerinin ısıl karakteristikleri, taşınımsal ısı transferi, kendi-kendine-ateşleme sıcaklığı.

NOMENCLATURE

A_{mol}	Number of moles of the propellant
C_p	specific heat capacity of barrel material
C_v	Specific heat coefficient of propellant gases
D	Inner diameter of the barrel
h_{air}	heat convection coefficient of surrounding air
h_g	heat convection coefficient of combustion gases
k	thermal conductivity of barrel material
m_B	initial mass of propellant
r	radial coordinate
P	Pressure of propellant gases
R	Universal gas constant
R_i	Inner radius of barrel
R_o	Outer radius of barrel
t	time
T	Temperature
T_g	temperature of the combustion gases
T_∞	Surrounding air temperature
U	Velocity of the projectile at time t
V_B	Combustion chamber volume
x	Distance which the projectile moved at time t
z	Percentage of the burned propellant

Greek symbols

α	thermal diffusivity of barrel material
ρ	Density of the propellant gases
γ	Specific heat ratio of propellant gases
ρ_b	density of barrel material
η	Covolume of the propellant gases

Subscript

j	Spatial position

Superscript

n	Time

INTRODUCTION

Introduction of the high energy content propellants in gun and rifle constructions leads to the importance of the barrel wear and erosion and the safety problems. The problems of wear and erosion of the barrels are studied extensively in the literature. It is found that the life of the barrel depends on the mechanical and thermal stresses occurred in the barrels during firing. Metallurgical structure of the barrel, chemical composition and geometrical design of the propellant, mechanical and geometrical structure of gun tubes and projectiles are the main parameters for life predictions and safety of guns (Kolkert et al., 1986; Huang et al., 2007; Elbe, 1975; Moeller and Bossert, 1973).

Kolkert et al. (Kolkert et al., 1986) worked on one-dimensional heat conduction model on a 20 mm barrel and a 0.50 caliber gun barrel without any comparison with experimental results. They modeled the problem for a single-shot which is quite important for the accuracy of the gun. Small deviations in angle of fire will cause significant error in the multiple shot analyses due to its accumulation. Huang et al. (Huang et al., 2007) have studied on gun barrel materials to obtain a lighter and longer life for a 5.56 mm rifle barrel. They extended their methods to cover the multi-shot heat transfer. The heat transfer coefficients of the barrel materials are accepted constant. External barrel temperature of a 5.56 mm M16 rifle has been worked by Elbe (Elbe, 1975). His measurements cover the temperature distribution along the barrel length depending on the shot number per firing sequence. Moeller and Bossert (Moeller and Bossert, 1973) and Blecker (Blecker, 1974) measured the inner and outer surface temperatures of the barrel of a 7.62 mm machine gun during sustained firing. Chen and Liu (Chen and Liu, 2008) modeled the problem of heat transfer from combustion gases to the inner surface of the barrel to find out the heat flux. They measured outer surface temperatures of the barrel and used them for inverse estimation of the heat flux to the surface of the barrel.

Mishra et al. (Mishra et al., 2010) worked on the computation of gun barrel temperature variation with time and its experimental validation. Experiments were carried out on a 155 mm, 52 caliber gun barrel and the barrel was assumed to be uniformly thick at any cross section along its axis. Moxnes (Moxnes, 2002) generated a model to estimate the thermodynamic characteristics of combustion gases in a barrel including convective heat transfer coefficient. Değirmenci and Dirikolu (Değirmenci and Dirikolu, 2012) studied on a thermo-chemical approach for the determination of convection heat transfer coefficient in a gun barrel. Shelton et al. (Shelton et al., 1973) studied fluid mechanics and heat transfer aspects of erosion in gun barrels. Shaliyev et al. (Shaliyev et al., 2006) studied experimentally the temperature dependence of thermal characteristic of high quality steels.

In this paper, a one-dimensional unsteady heat transfer calculation method is presented to calculate the heat transfer in a machine gun barrel during sustained firing. The method is extended to cover cook-off temperature calculations of the machine gun. As an example, application is solved for a 7.62 mm M60 Machine gun barrel with 7.62 mm M80 ammunition. For this case, the thermodynamic characteristics of combustion gases and convective heat transfer coefficient in the barrel are calculated by means of Internal Ballistic Code AKÇAY (Akçay, 1992). This code based mainly on Resal’s equation is capable of calculating the projectile displacement, projectile velocity, percentage of the propellant burned, combustion gas temperature, combustion gas density and pressure behind the projectile base and in the combustion chamber, depending on time at any point in the gun barrel. The shape of the propellant might be spherical or multi perforated cylindrical geometry. Gun barrel material thermal characteristics are taken non-homogenous in the calculations.

STATEMENT OF THE PROBLEM AND GOVERNING EQUATIONS

During the interior ballistic cycle in a barrel, an amount of heat is generated due to combustion of the propellant. Some part of this heat that accepted as a loss is transferred into the structures of barrel and projectile. The increase in the temperature of barrel and projectile causes thermal stresses in these components. Thus lead to the changes in dimensional tolerances result in a loss of firing accuracy. Furthermore, the particles of the hot gases moving in the barrel erode the surface of the heated barrel more easily. As a consequence, the temperature of the barrel becomes a main parameter for both of the firing accuracy and the gun barrel erosion.

The elements of heat transfer phenomena in gun barrels can be summarized as follows (Kolkert et al., 1986):

(a) Forced convection in two-phase flow during combustion and projectile travel. The boundary layer effects of the heat transfer near the inner wall of the barrel,
(b) Radiation from the burning propellants and hot combustion gases,
(c) Conduction through the hot gases to the barrel wall,
(d) Dissipation of heat in the barrel,
(e) Heat transfer from the outer surface of the barrel to the surroundings.

Radial Heat Transfer Model

For solving the heat transfer problem in a barrel, the heat transfer model for circular pipes which is formulated in cylindrical coordinates can be used, as shown in Fig.1.

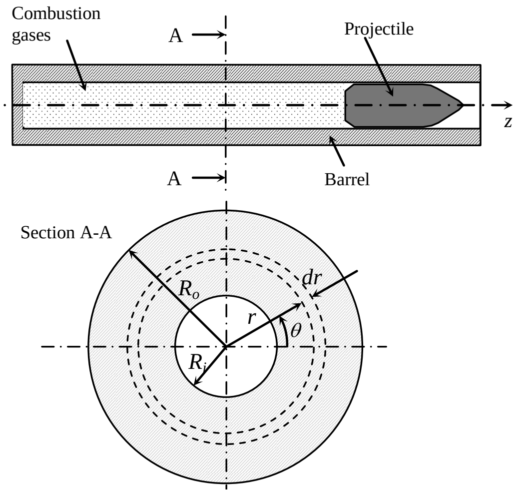

Figure 1. Cylindrical coordinates for heat transfer problem in a barrel

Heat transfer due to radiation may be negligible in this approach. During the internal ballistic cycle, the radial temperature gradient $\partial T/\partial r$ is much greater than that of the axial temperature gradient $\partial T/\partial z$. The problem is also axially symmetrical. So that, the heat transfer equation in any section sufficiently far from the ends of the barrel can be arranged in cylindrical coordinates as following Fourier equation:

$$\frac{\partial T}{\partial t} = \alpha(T)\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{k(T)}\frac{\partial k(T)}{\partial T}\left(\frac{\partial T}{\partial r}\right)^2\right] \qquad (1)$$

where, $\alpha(T)$ represents the thermal diffusivity as a function of the thermal conductivity of barrel, $k(T)$, and the density, ρ_b, and the specific heat capacity, $C_p(T)$, of barrel material as following:

$$\alpha(T) = \frac{k(T)}{\rho_b C_P(T)} \qquad (2)$$

The density of barrel material is considered as a constant.

Initial and Boundary Conditions

The initial condition is

$$T(r,t)\big|_{t=0} = T_\infty \qquad \text{for} \qquad R_i \le r \le R_o \qquad (3)$$

where, T_∞ represents the temperature of the surrounding air during firing.

The boundary conditions for inner and outer surfaces of the barrel are given, respectively, as following:

$$\text{At} \quad r = R_i \quad \text{and} \quad t > 0, \qquad h_g\left(T_g - T_i\right) = -k\left.\frac{\partial T}{\partial r}\right|_{r=R_i} \qquad (4)$$

$$\text{At} \quad r = R_o \quad \text{and} \quad t > 0, \qquad h_{air}\left(T_\infty - T_o\right) = -k\left.\frac{\partial T}{\partial r}\right|_{r=R_o} \qquad (5)$$

where T_i and T_o are the temperatures at the inner and outer surfaces of the barrel, respectively; k is the heat conduction coefficient of the barrel material; h_g is the heat convection coefficient of combustion gases; h_{air} is the heat convection coefficient of the surrounding air and T_g is the temperature of the combustion gases.

NUMERICAL SOLUTION METHOD

Governing Equation

Eq.(1) is elliptic in space domain and parabolic in time domain. Therefore using a FTCS (Forward Time Central Space) finite difference discretization method (Hoffmann and Chiang, 1989) one obtains

$$\frac{T_j^{n+1} - T_j^n}{\Delta t} = \frac{\alpha_j^n}{\Delta r}\left[\frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{\Delta r} + \frac{T_{j+1}^n - T_{j-1}^n}{2r_i} + \frac{\left(k_{j+1}^n - k_{j-1}^n\right)}{4k_j^n}\frac{\left(T_{j+1}^n - T_{j-1}^n\right)}{\Delta r}\right] \qquad (6)$$

or rearranging

$$T_j^{n+1} = \frac{T_{j-1}^n + \left(M_j^n - 2\right)T_j^n + T_{j+1}^n}{M_j^n} + \left(\frac{C_j^n}{2r_j} + \frac{k_{j+1}^n - k_{j-1}^n}{4M_j^n k_j^n}\right)\left(T_{j+1}^n - T_{j-1}^n\right) \qquad (7)$$

with,

$$M_j^n = \frac{(\Delta r)^2}{\alpha_j^n \Delta t} \qquad (8)$$

$$C_j^n = \frac{\alpha_j^n \Delta t}{\Delta r} \qquad (9)$$

Where, subscript j indicates radial position and superscript n denotes the time step, as shown in Fig.2.

Initial and Boundary Conditions

The initial condition is

$$T_j^0 = T_\infty \qquad \text{for} \qquad j = 1,2,\ldots N \qquad (10)$$

Neumann type boundary conditions in equations (4) and (5) are difficult to be applied with given forms, since they contain the derivative of unknown temperature. Instead, a heat balance equation for a narrow region with a thickness Δr adjacent to the barrel surfaces can be written as following (Değirmenci and Dirikolu, 2012):

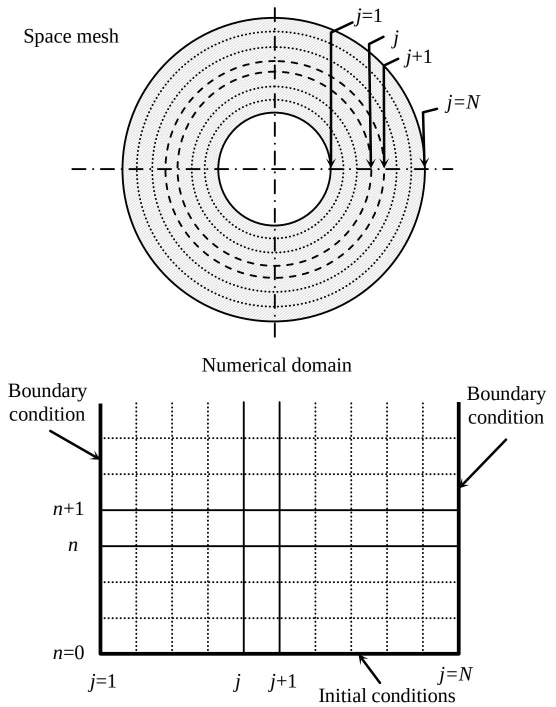

Figure 2. Numerical grid at any cross section

At the inner surface of the barrel:

$$2\pi R_i h_g \left(T_g - T_i\right) = 2\pi R_i \frac{\Delta r}{2} \rho_b C_p(T) \frac{\partial T}{\partial t} + 2\pi \left(R_i + \frac{\Delta r}{2}\right) \left(-k \left.\frac{\partial T}{\partial r}\right|_{r=R_i+\frac{\Delta r}{2}}\right) \tag{11}$$

At the outer surface of the barrel:

$$2\pi R_o h_{air} \left(T_\infty - T_o\right) = 2\pi R_o \frac{\Delta r}{2} \rho_b C_p(T) \frac{\partial T}{\partial t} + 2\pi \left(R_o - \frac{\Delta r}{2}\right) \left(-k \left.\frac{\partial T}{\partial r}\right|_{r=R_o-\frac{\Delta r}{2}}\right) \tag{12}$$

Finite difference form of above equations can be written respectively for the inner and the outer surfaces, as follows:

$$T_1^{n+1} = T_1^n + \frac{2\alpha\left(T_1^n\right)}{\Delta r^2} \Delta t \left[\left(T_2^n - T_1^n\right) + \frac{h_g}{k}\left(T_g^n - T_1^n\right)\Delta r + \frac{\left(T_2^n - T_1^n\right)}{2R_i}\Delta r\right] \tag{13}$$

$$T_N^{n+1} = T_N^n - \frac{2\alpha\left(T_N^n\right)}{\Delta r^2} \Delta t \left[\left(T_N^n - T_{N-1}^n\right) + \frac{h_{air}}{k}\left(T_N^n - T_\infty\right)\Delta r - \frac{\left(T_N^n - T_{N-1}^n\right)}{2R_o}\Delta r\right] \tag{14}$$

where $T_1 = T_i$ and $T_N = T_o$ are the inner and outer surface temperatures, respectively;

Numerical Solution Procedure

In order to calculate entire temperature distribution at any time step Eq. (7) is used for internal points, and Eqs. (13), (14) are for the surface boundary points. Eq. 7 has a convergent solution only for the values of $M \geq 2$. Thus, the time step is calculated from Eq.8 as following:

$$\Delta t \leq \frac{(\Delta r)^2}{2\alpha_j^n} \tag{15}$$

Eqs. (7), (13) and (14) are solved together for an internal ballistic cycle for the duration of $0 \leq t \leq t_0$. During the interior ballistic solution of the problem, basic inputs come from combustion of the propellant. Consequently the heat flux and the temperature of the combustion gases and thermal characteristics of barrel material are taken as functions of time.

The temperature of the gases at any point in the cross section of the barrel can be calculated as following:

$$T_g = \frac{P\left[V_B - m_B\left(z\eta + \frac{1-z}{\rho}\right) + \frac{\pi D^2 x}{4}\right]}{\left(A_{mol} m_B z R\right)} \tag{16}$$

Where P is the pressure of propellant gases behind projectile in the barrel, V_B is the combustion chamber volume, m_B is the initial mass of propellant, z is the percentage of the burned propellant, η is the covolume of the propellant gases, ρ is the density of the propellant gases, D is the inner diameter of the barrel, x is the distance which the projectile moved at any time t, A_{mol} is the number of moles obtained by means of the solution of the combustion problem of the propellant and R is the universal gas constant (Shaliyev et al., 2006). The heat convection coefficient of combustion gases is given as

$$h_g = f(x, \rho, U, C_v, \gamma) \tag{17}$$

In addition to the above explained parameters U is the velocity of the projectile at time t, C_v is the specific heat coefficient of propellant gases and γ is the ratio of specific heat constants of the propellant gases.

The natural convection heat transfer coefficient of air around a barrel for buoyant laminar flow has been expressed by Conroy et al. (Conroy et al., 2001) as

$$h_{air} = 1.32\left(\frac{T_o - T_\infty}{2R_o}\right)^{0.25} \tag{18}$$

APPLICATION OF THE METHOD

As an example, heat transfer of a 7.62 mm M60 machine gun barrel has been studied. In order to calculate the thermodynamic properties of combustion gases of the propellant during internal and intermediate ballistic cycle, Internal Ballistic Code AKÇAY (Akçay, 1992) is used. Initial air temperature is considered 25°C and the convection coefficient of the air is $h_{air} = 25\ W/m^2K$. The properties of the combustion gases of double base propellant used in 7.62×51 mm ammunition are; $C_p = 1.74\times10^3\ m^2/s^2K$, $C_v = 1.38\times10^3\ m^2/s^2K$, $\gamma = 1.26$. For 7.62 ×5 1 mm ammunition $A_{mol} = 42.56\ mol/kg$ is obtained. Universal gas constant is $R = 8.31434\ J/mol\,K$. The predicted temperature of the propellant gases in the barrel reaches up to 2828 °K.

The variation of the calculated convective heat transfer coefficients along the length of barrel is given in Fig.3. For these calculations all the parameters are assumed to be function of the time.

In order to solve Eq.(7), the thickness Δr is accepted as a minimum value of 9.6×10^{-6}m, Δt is calculated from Eq.(15) as 4×10^{-6}seconds.

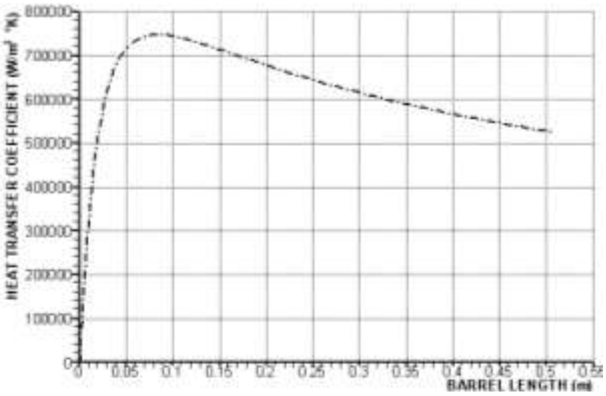

Figure 3. Variation of convective heat transfer coefficient for M60 Machine Gun barrel

SAE stainless steel is generally used in gun barrel production. Steels have temperature dependent metallurgical structure and their thermal characteristics such as heat capacity and thermal conductivity are functions of temperature. Shaliyev and et al. (Shaliyev and et al., 2006) have studied on this matter in detail and they obtained thermal characteristics depending on the temperature of the stainless steels. The chart for the temperature dependent thermal characteristics of SAE 4130 steel is also given by Blecker (Blecker, 1974). This information have been reviewed, rearranged and used as functions of material temperature in this study, as follows;

$$C_p(T) = \begin{cases} 472.6 - 0.00123.T + 0.0003T^2 & T < 977^O K \\ 758.957 + 8.25(T - 977) & 977 \le T \le 1069^O K \\ 1517.915 - 15.02(T - 1069) & 1069 \le T \le 1133^O K \\ 556.569 + 0.1470(T - 1133) & 1133 \le T \le 1477^O K \end{cases} \quad (19)$$

$$k(T) = \begin{cases} 40.59 + 0.0172.T - 0.0000285T^2 & T < 1116^O K \\ 24.29 + 0.006901060(T - 1116) & T \ge 1116^O K \end{cases} \quad (20)$$

The temperature distribution at the inner surface of the 7.62 mm M60 machine gun barrel has been calculated as a function of rate of fire by means of the application above procedures. During firing, when the bullet is in the barrel, the temperature at the inner surface of the barrel increases up to 897 K. Between the times that a bullet leaves the barrel and a new bullet is fired, the barrel starts to cool down. The results of theoretical calculations of the upper and lower temperature at the inner and the outer surface of the M60 Machine gun barrel are given in Fig.4 compared with the experimental data. The experimental values are measured only up to the 125 rounds (Moeller and Bossert, 1973; Blecker, 1974).

For these calculations the ambient temperature was 25°C. The increment of the lower temperature of the inner surface is parabolic up to 50 rounds and then becomes nearly a linear function of the number of rounds. The lowest and highest temperature of the inner surface reaches to the values of 521K and 880 K, respectively, at 150 rounds. The difference between the upper and lower temperature of the inner surface is 359°C. At the firing round 50 the calculated outer surface temperature of the barrel is around 356 K. The agreement between the theoretical and experimental values of minimum temperature at the inner surface is quite good but the theoretical values of maximum temperature up to the 5 shots are 5% over predicted.

The time history of heating and cooling phases of the barrel's inner surface is shown in Fig.5 for 23 rounds firing and in Fig.6 for 200 rounds firing. The temperature distributions at a cross section of M60 Machine gun barrel are shown in Fig.7 and Fig.8. The curves show a non linear characteristic of the temperature change along the barrel thickness before the next firing. The temperature increase at the inner surface is more than the increment at the outer surface. The temperature of 517 K measured at the outer surface of the barrel after first 125 burst firing is higher than the calculated value of 441.6 K. At the end of 200 rounds of firing, the predicted temperature of the outer surface reaches up to 510.7 K from 298 K. The large difference between the theoretical and the experimental values of the outer surface temperature at 125 burst firing may basically occur due to the one-dimensional solution model. Because in the case of a real gun the heat transfer problem is three-dimensional and heat flows

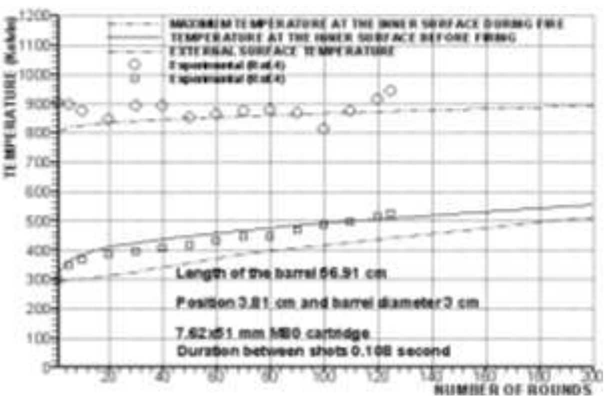

Figure 4. Temperature versus number of rounds at 7.62 mm M60 Machine Gun

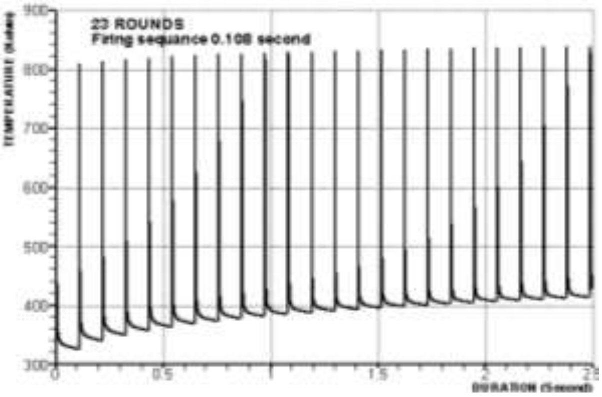

Figure 5. 7.62 mm M60 Machine Gun barrel inner surface temperature

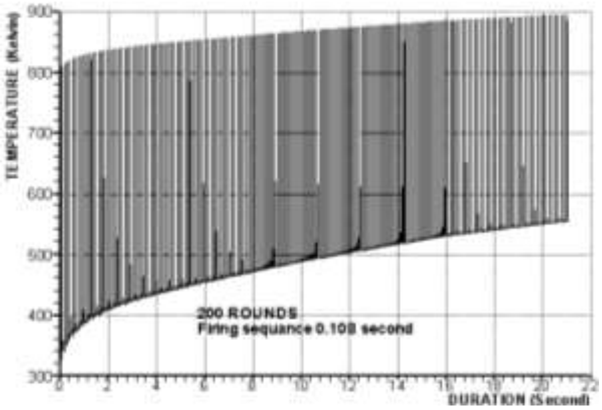

Figure 6. 7.62 mm M60 Machine Gun barrel inner surface temperature

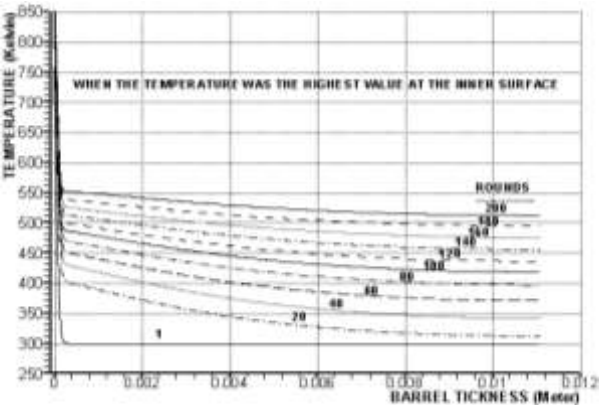

Figure 7. Temperatures at a cross section of the barrel (x = 3 cm) for the highest temperature at the inner surface

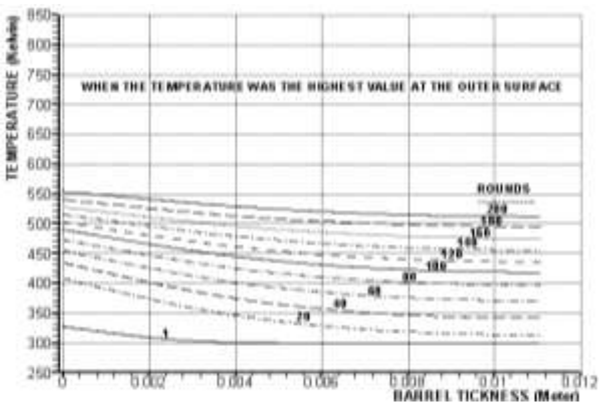

Figure 8. Temperatures at a cross section of the barrel (x = 3 cm) for the highest temperature at the outer surface

axially down to the length of the barrel and to the other gun assemblies. Another reason may be the difference in the metallurgical composition of the barrel material used in the experiments and in the calculations. Free convection also causes peripheral temperature difference on the outer surface of the barrel along the barrel.

The excessive temperature increases in the machine gun barrels cause a decrease both in the strength of barrel material and bending. During the serial firings, excessive heating of the combustion chamber material also causes an increase in the temperature of the propellant which results in self ignition of the propellant and unexpected firings. All of these effects due to the temperature increases in gun barrel materials have to be considered during gun barrel design.

SELF IGNATION OF THE PROPELLANTS

One of the serious concerns when firing a small caliber or a large caliber gun is the cook-off phenomena. Cook-off, sometimes called as auto-ignition or self ignition can occur when enough heat from the barrel transfers to cartridge round, causing unintended ignition of the propellant or the explosive (Yuhas et al., 2009). Gun bore receives large amounts of heat resulting from combustion of ammunition propellants and from the friction between the projectile surface and the gun bore during firing. Before a new round is fired the barrel has a limited time to cool down. Some part of the heat is transferred to the surrounding atmosphere by means of natural convection and radiation, rest of the heat can cause the temperature of the barrel to increase. During sustained firing, heat accumulated in the barrel can cause temperature reach to the cook-off temperature. Once the cook-off temperature is reached, propellants from the new round will self ignite when sufficient contact time between new round and the hot barrel bore surface is given (Wu et al., 2008).

Double base propellant is used in 7.62×51 mm M80 ammunition. The measured ignition temperature for the propellant used in M80 ammunition is $165°C$. The brass material cartridge case creates heat isolation between the chamber and propellant. For 7.62 mm rifle chamber, this heat isolation causes around $50°C$ temperature decrease of the propellant temperature. In this case, one can expect self ignition of propellant may occur when the temperature of the inner surface of the chamber reach to the value of $215°C$. In Fig.4, theoretical inner surface temperature calculation of a 7.62 mm M60 machine gun barrel is given. Dotted lines show minimum temperature values, the lines show maximum temperature values of the inner surface of the barrel depending on the number of rounds during firing. In this specific design, the self ignition of the propellant is expected for 130 rounds firing. According to the experimental results (Moeller and Bossert, 1973; Blecker, 1974) self ignition can occur around 120 rounds for M60 machine gun. The theoretical results are quite close to the experimental results.

CONCLUSIONS

A general one-dimensional axially symmetrical unsteady heat transfer calculation model is prepared and used for the heat transfer calculation of 7.62 mm M60 Machine gun barrel during sustained firing. Although the solution of heat transfer in 7.62 mm M60 machine gun barrel is demonstrated, this model can further be used in similar barrels such as cylindrical small and large caliber gun barrels. On the basis of the results obtained from theoretical analysis and finite difference calculations; the agreement between theoretical and experimental results are quite satisfactory. Further by using this method the cook-off conditions of the guns can also be predicted which a very important parameter for the gun design is.

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