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TRANSIENT HEAT TRANSFER ANALYSIS OF A MACHINE GUN BARREL

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Abstract. *The heat from propellants contributes to increased gun barrel temperature during a firing sequence. High values of barrel temperature could cause gun malfunctioning thus jeopardizing the user's safety in addition to accelerated barrel erosion. Therefore, it is desirable to determine the temperature distribution in rapid firing gun barrels. In this contribution, a numerical solution for the one-dimensional transient heat transfer problem across a machine gun barrel is presented and discussed. The model considers the thermal conductivity and the specific heat of the barrel material as functions of the barrel temperature, and the interior wall boundary condition is computed from the interior ballistics of the cartridge via the Baer-Frankle method employed by PRODAS software tool. The numerical solution is then achieved through a finite volume method code implemented in the MATLAB software program. Results obtained in several burst firing situations such as rate of fire, number of rounds per burst and time between bursts were then critically analyzed in order to verify the maximum number of rounds allowed before the cook off temperature is attained in each situation. The results were also compared to the ones obtained with a simpler model that considers constant thermal conductivity and constant specific heat. The methodology here advanced could be employed in future studies concerning gun safety and barrel erosion as well as in trade studies of gun barrels materials.*

Keywords: *machine gun, transient heat transfer, prodas, matlab.*

1. INTRODUCTION

The knowledge of gas bore temperature and heat transfer in gun barrels is important mainly for the prediction of self-ignition of rounds loaded into a hot barrel and for the determination of erosion rates at the commencement of rifling. During the firing, gun bore surface receives large amounts of heat due to the combustion of the propellant and, although time between rounds allows for cooling of the barrel, only a small amount of heat is effectively transferred to the environment by convection and thermal radiation, which results in increasing surface temperatures as rounds are fired in sequence. The probability that a projectile will ignite prematurely (cook-off) given a sufficient time increases at high temperatures. For example, cook-off in 120 mm guns is attained in 120 seconds if the combustible cartridge case is in contact with steel at 200°C, whereas at 250°C self-ignition takes only a few seconds (Lawton and Klingenberg, 1996). For machine guns and other light weapons, however, the explosive charge is protected by a brass cartridge case and does not remain inside the barrel for large amounts of time, and consequently cook off temperatures may be higher than the ones for cannons and howitzers. On the other hand, since hardness and strength of metals are known for decrease very quickly at high temperatures, the advantage of higher steady bore temperatures that may be sustained in machines guns is offset by the very high wear rates and barrel life reduction that follows. Therefore, several authors have conducted researches in heat transfer applied to gun barrels in order to address these issues.

Lawton (2001) derived a simple equation of the Arrhenius type relating the wear per round to the initial temperature, maximum surface temperature and the erosivity of the propellant. The equation was verified by experiments and by data on the wear rates of numerous guns and propellant combinations.

Huang *et al.* (2007) investigated the feasibility of a ceramic gun barrel due its potential for lighter weight and longer tube life despite of the hazardous combination of thermal and structural loading that can result in a severe thermal stress state at the inner barrel surface. They presented a finite element analysis focused on the thermal effects during the firing of a 5.56mm ceramic gun barrel. The single shot thermal response was investigated in detail, and results were obtained describing the inner wall elevated temperature, the temperature distribution, as well as the barrel surface temperature gradient. Also, multiple shot thermal modeling was performed for a burst firing of 200 rounds over a period of 2 minutes. The results obtained were used to describe the transient heating of the gun tube over a long period of continuous firing and experimental results were then compared with the simulation.

Wu *et al.* (2008) analyzed the heat transfer in a 155 mm mid-wall cooled compound gun barrel. The finite elements method was employed to validate the theoretical analysis showing that natural air cooling is ineffective to transferring heat out of the barrel and that forced mid-wall cooling has great extraction capabilities. The problem of manufacturing

such mid-wall cooled compound gun barrel was not addressed. A heat balance estimated typical cook-off temperatures to be around 200°C.

Gonzaga *et al.* (2010) performed a theoretical analysis of the heat transfer in gun barrels and the resulting model was analytically solved thus furnishing the transient temperature distribution for the situation of external wall cooling, and therefore producing benchmark results with a very low computational effort. A few situations related to barrel external natural cooling were simulated and the results then critically compared to the ones obtained through the finite elements method.

Salazar (2011) performed a theoretical analysis of the one-dimensional heat transfer in a 155 mm gun barrel and the resulting model was analytically solved thus furnishing the transient temperature distribution for the situation of convective cooling at the walls. Results obtained enabled the validation of the numerical solutions by Wu *et al.* (2008) which employs the finite elements method, and allowed for an estimate of the maximum number of rounds that could be fired before attaining the cook-off temperature, under external convective cooling with natural air and forced liquid. In addition, the wear effect studied by Lawton (2001) was taken into account and available data for the ARM198 howitzer from the Ecuadorian Army were used in the simulations to determine the limiting number of rounds that could be fired in real-world applications.

Hill and Conner (2012) developed a transient heat transfer model that address the thermal management problem of machine gun barrels and rapid trade studies of barrel geometry and material. They solved the one-dimensional temperature profile through the thickness of the barrel at a specified axial location by means of a finite-difference model using the Mathematica software. Their model incorporates features such as convection with variable heat transfer coefficients at both the interior and exterior walls, radiative cooling at the exterior wall and arbitrary burst firing schedules. The input data for the interior wall boundary condition was computed from the interior ballistics software PRODAS, developed and marketed by Arrow Tech Associates, Inc. An illustration of the methodology was provided through the examination of burst firings of the M80 cartridge from an M60 machine gun and results compared to available experimental data.

Akçay and Yükselen (2014) presented a one-dimensional unsteady heat transfer numerical calculation for a machine gun barrel during sustained firing. The method is based on a finite differences scheme and was extended to cover cook-off temperature calculations. An application was solved for a 7.62 mm M60 machine gun barrel with 7.62 mm M80 ammunition where the thermodynamic characteristics of combustion gases and convective heat transfer coefficient in the barrel were calculated by means of an internal ballistic code developed by one of the authors. They concluded that self-ignition of propellant may occur when the temperature of the inner surface of the chamber reaches the value of 215°C.

In order to improve the life of gun barrels influenced by periodic transient thermal shock during firing, Feng *et al.* (2019) established a mathematical model of two-dimensional nonlinear heat conduction of a gun barrel to study the temperature field and its variation rule. The governing equations and boundary conditions were linearized by Kirchhoff's variation, and an implicit finite difference scheme was employed in the solution of the problem. Based on the numerical results of the classic interior ballistics, the authors presented the temperature distribution of a 12.7 mm machine gun barrel during 120 successive firing rounds. The temperature field of the external surface of the barrel was evaluated and the variation law of the temperature field was obtained. Comparison with experimental results showed good agreement with the simulation thus providing a base for studies of new barrel materials and coatings.

In this contribution, a one-dimensional transient heat transfer model for an M2 HB Browning machine gun from the Brazilian Army inventory is numerically solved by a finite volume code developed in MATLAB®. The model considers the thermal conductivity and the specific heat of the barrel material either constant or as functions of the barrel temperature, and the interior wall boundary condition is computed from the interior ballistics of the .50 BMG (12.7 mm) cartridge via the Baer and Frankle (1962) method employed by PRODAS software tool.

2. MATHEMATICAL MODEL AND INPUT DATA

We consider a machine gun barrel in the form of a hollow cylinder of inner and outer radius given by R_i and R_o , respectively, in which temperatures gradients in both axial and azimuthal directions are negligible when compared to the ones in the radial r direction. The barrel material is AISI 4140 steel and the barrel thermal conductivity k and specific heat c are assumed to vary with barrel temperature while its density ρ is held constant. The gun barrel is cooled at its outer surface by convection and radiation to an ambient held at a constant temperature T_∞ . The barrel surface emissivity is ε and σ is the Stefan-Boltzmann constant. On the interior surface of the barrel, we consider convective heat transfer between the propellant gas flow and the inner surface. The temperature of the bore gas, T_{gas} , is taken as the mean value at the cross section of the tube. Initially, the temperature throughout the barrel is considered to be equal to the ambient temperature. Accordingly, the radial transient temperature distribution $T(r, t)$ is governed by the following heat transfer equation subjected to the aforementioned boundary conditions and initial condition:

$$\rho c(T) \frac{\partial T}{\partial t} = \frac{1}{r} \left[k(T) \frac{\partial T}{\partial r} + r \frac{\partial}{\partial r} \left(k(T) \frac{\partial T}{\partial r} \right) \right] \quad (1)$$

$$k(T) \frac{\partial T}{\partial r} = h_{int} (T - T_{gas}) \quad , \quad r = R_i \quad (2)$$

$$k(T) \frac{\partial T}{\partial r} = h_{ext} (T_{\infty} - T) + \epsilon \sigma (T_{\infty}^4 - T^4) \quad , \quad r = R_0 \quad (3)$$

$$T(r) = T_{\infty}, \quad t = 0, \quad R_i \leq r \leq R_0 \quad (4)$$

According to Robbins and Raab (1988), the internal heat transfer coefficient of a gun bore, h_{int} , can be approximated by

$$h_{int} = h_0 + \lambda_N \bar{\rho} c_p \bar{v} \quad (5)$$

where h_0 is the free convective heat transfer coefficient for the air inside the bore, $\bar{\rho}$ is the mean density of the propellant gas, c_p is the specific heat of the propellant gas, \bar{v} is the mean gas velocity at a fixed wall position, and λ_N is the dimensionless Nordheim friction factor given by

$$\lambda_n = [13,2 + 4 \log_{10}(200 R_i)]^{-2} \quad (6)$$

The external heat transfer coefficient, h_{ext} , is evaluated from the average Nusselt number, \overline{Nu}_D , for a long horizontal cylinder (Churchill and Chu, 1975), which is valid for a range of Rayleigh number, Ra_D , up to 10^{12} , given by

$$h_{ext} = \frac{k_{air} \overline{Nu}_D}{D} = \frac{k_{air}}{2 R_0} \left\{ 0,60 + \frac{0,387 Ra_D^{1/6}}{\left[1 + \left(\frac{0,559}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2 \quad (7)$$

where k_{air} is the thermal conductivity of the ambient air, D is the outer diameter of the barrel at the specified location, and Pr is the Prandtl number.

For AISI 4140 steel, surface emissivity is taken as 0.6 (Kus *et al.*, 2015) and density is taken as 7850 kg/m³ (Azom, 2019), while thermal conductivity and specific heat variation with barrel temperature are obtained by means of GetDataGraph software applied to graphical data presented by Rothman (1988). These data are shown in Figure 1.

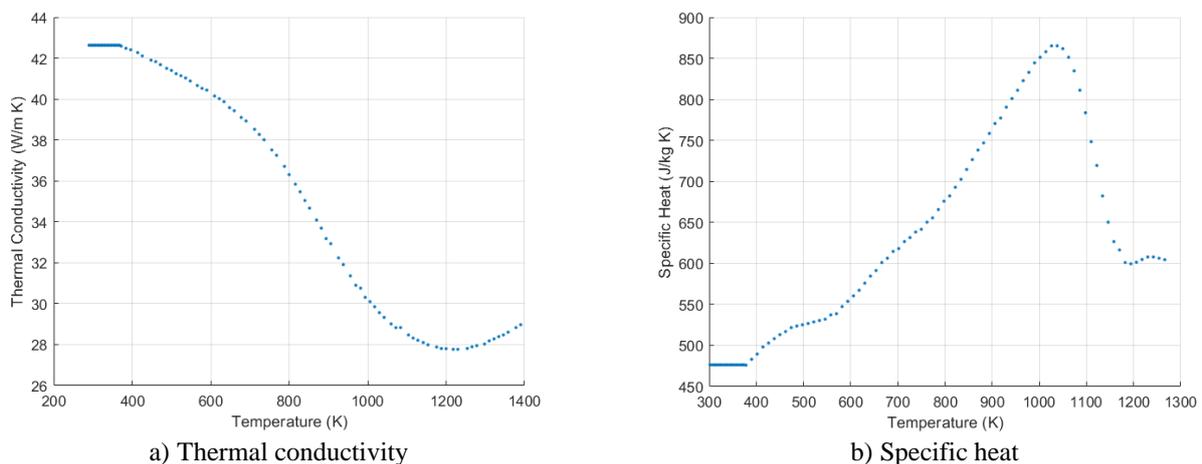


Figure 1. Thermal properties of AISI 4140 steel as a function of temperature.

The Baer and Frankle (1962) lumped ballistic model allows for the determination of interior ballistics properties, such as average gas temperature, gas pressure at the projectile base, gas pressure at the gun breach, projectile velocity and displacement, propellant mass burnt fraction, among others, all as functions of time for a specific ammunition. Therefore, in order to use this model, it is mandatory that these properties be assumed to be independent of barrel temperature and identical for each round shot. Consequently, the bore gas temperature and internal heat transfer coefficient, h_{int} , needed in Eq. (2) are considered to be functions of time only and are readily computed from PRODAS software in the following manner: The gas at the gun breach is assumed to have zero velocity and the velocity of the gas at the travelling projectile base is assumed to be identical to the projectile velocity (Hill and Conner, 2012). Then, the

mean cross section flow velocity of the gas, \bar{v} , at a specified axial position is determined by taking the average between these two values, i.e., by considering half of the value of the projectile velocity. In a similar fashion, since PRODAS provides the fraction of propellant mass burnt as a function of time, and the initial propellant mass is known, $\bar{\rho}$ is calculated from the ratio between the mass of propellant burnt and the gas volume from the breach to the projectile base. As far as specific heat of the propellant gas is concerned, we take a constant value of 1050 J/kgK due to the difficulties associated to its precise determination as a function of temperature, pressure and combustion products composition (Hill and Conner, 2012). The free convective heat transfer coefficient h_0 was assumed constant and equal to 10 W/m²K throughout our simulations.

Tables 1, 2 and 3 summarize the results obtained from PRODAS software when applied to the specific case of an M2 HB Browning machine gun and .50 BMG cartridge. For the present analysis, we have chosen an axial position located at 0.155 m from the gun breach, where the external diameter of an actual barrel was measured by the authors as being 0.04905 m.

The external heat transfer coefficient h_{ext} is calculated as a function of temperature as follows: for $T_\infty = 303.15$ K and $D = 0.04905$ m, Eq. (7) is employed with Ra_D and Pr evaluated at film temperature. Thermophysical properties for air at any film temperature ranging from 303.15 K up to 600 K are obtained by interpolation on tabular data available in Incropera and DeWitt (2007). Figure 2 shows the exterior heat transfer profile thus obtained as a function of film temperature at 0.155 m from the breach.

However, by considering that the maximum rate of fire for the M2 HB Browning is 550 rounds per minute, elapsed time between two consecutive rounds is found to be 0.1091 s, but, an inspection on Table 3 reveals that the projectile leaves the muzzle at 0.002414 s and therefore internal ballistics calculations end at this point. Consequently, the gas pressure, gas temperature and gas density distributions inside the bore after a round is fired are unknown once the projectile leaves the muzzle. As such unknown data is crucial to the numerical simulations, we assume, based on Hill and Conner (2012), that these distributions inside the bore decay exponentially to their respective values at ambient conditions between two consecutive rounds. Accordingly, we considered that the gas temperature and the mean density of the propellant gas are given approximately by the following expressions after the projectile leaves the muzzle:

$$T(t) = 303.15 + 1371.3 e^{-\gamma(t-0.002414)} \quad (8)$$

$$\bar{\rho} = 1.1614 + 144.7216 e^{-\delta(t-0.002414)} \quad (9)$$

Table 1. M2 HB Browning .50 data

Barrel Length, mm	828.04
Chamber Volume, cm ³	16.59
Bore Diameter, m	0.0127
Bore Area, cm ²	1.30102

Table 2. Propellant characteristics for the .50 BMG cartridge from PRODAS database

Mass, g	15.4221
Co-volume, m ³ /kg	0.0011
Density, kg/m ³	1619.3

Table 3. Internal ballistics results as a function of time for the .50 BMG cartridge computed with PRODAS software.

Time ms	Travel cm	Velocity m/s	Base Pressure MPa	Breach Pressure MPa	Temperature K	Mass Burnt Fraction
0.06	0.00006	0.066	12.820	12.820	3280.15	0.001
0.24	0.02289	3.101	25.202	25.202	2944.25	0.007
0.36	0.07815	6.034	38.026	38.026	2828.25	0.013
0.46	0.14780	7.748	52.830	52.830	2768.25	0.020
0.54	0.21338	8.605	68.422	68.424	2735.45	0.028
0.6	0.26687	9.258	83.026	83.028	2716.65	0.035
0.66	0.32744	11.469	100.771	100.775	2700.95	0.043
0.7	0.37959	14.892	114.580	114.588	2691.15	0.050
0.74	0.44896	20.113	130.089	130.105	2681.65	0.058
0.78	0.54317	27.343	147.311	147.344	2671.95	0.067
0.82	0.67065	36.786	166.140	166.207	2661.45	0.077
0.86	0.84063	48.622	186.317	186.450	2649.25	0.089
0.9	1.06298	62.989	207.405	207.653	2634.55	0.103
0.94	1.34977	81.395	228.518	228.975	2614.85	0.118
0.98	1.72052	104.560	247.864	248.681	2584.15	0.136
1.02	2.19070	131.056	264.390	265.761	2545.75	0.156
1.04	2.46688	145.229	271.305	273.033	2524.15	0.167
1.06	2.77189	159.876	277.262	279.403	2501.75	0.178
1.08	3.10662	174.944	282.213	284.824	2478.55	0.19
1.1	3.47187	190.379	286.133	289.270	2454.75	0.202
1.12	3.86830	206.127	289.019	292.737	2430.55	0.215
1.14	4.29650	222.134	290.890	295.240	2405.95	0.229
1.16	4.75693	238.350	291.784	296.811	2381.15	0.243
1.22	6.33462	287.606	289.217	296.496	2306.95	0.287
1.26	7.55025	320.152	284.117	293.000	2260.25	0.319
1.28	8.20662	336.216	280.819	290.516	2238.05	0.335
1.3	8.89494	352.108	277.124	287.633	2216.65	0.352
1.32	9.61487	367.805	273.099	284.415	2196.15	0.369
1.34	10.3660	383.294	268.805	280.919	2176.35	0.386
1.36	11.1478	398.560	264.296	277.194	2157.45	0.403
1.38	11.9600	413.595	259.618	273.283	2139.25	0.420
1.4	12.8020	428.391	254.813	269.224	2121.85	0.438
1.46	15.5020	471.189	239.995	256.493	2073.95	0.491
1.52	18.4509	511.350	225.217	243.539	2032.85	0.544
1.58	21.6329	548.908	210.871	230.736	1997.45	0.597
1.64	25.0327	583.961	197.126	218.246	1966.65	0.648
1.7	28.6356	616.629	184.040	206.130	1939.15	0.696
1.78	33.7314	656.684	167.615	190.576	1906.15	0.757
1.86	39.1325	692.999	152.319	175.694	1875.85	0.812
1.94	44.8100	725.832	138.104	161.484	1846.95	0.859
2.02	50.7371	755.416	124.947	147.981	1818.45	0.899
2.1	56.8887	782.007	112.831	135.233	1789.95	0.931
2.2	64.8592	811.424	99.135	120.447	1753.75	0.961
2.3	73.1045	837.055	87.027	107.038	1716.85	0.981
2.414	82.8040	862.172	75.151	93.571	1674.45	0.993

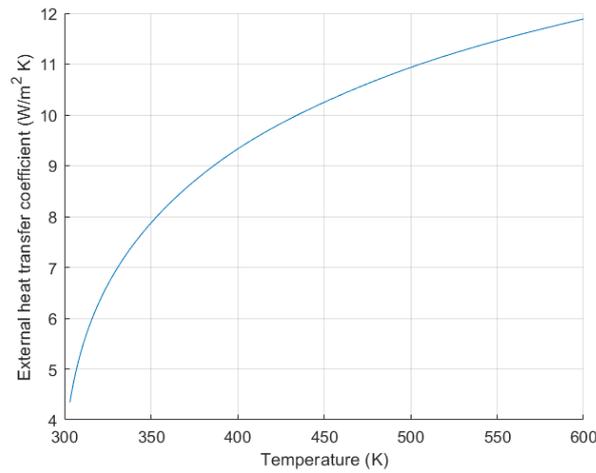


Figure 2. External heat transfer coefficient as a function of film temperature calculated from Churchill and Chu (1975) correlation for $T_{\infty} = 303.15$ K and $D = 0.04905$ m.

Several values for the exponents γ and δ in Eq. (8) and Eq. (9), respectively, were tested in the ranges $700 \text{ s}^{-1} \leq \gamma \leq 1000 \text{ s}^{-1}$ and $1000 \text{ s}^{-1} \leq \delta \leq 1300 \text{ s}^{-1}$, and each gas temperature distribution and each calculated internal heat transfer coefficient thus obtained was critically compared to their counterparts' curves reported by Hill and Conner (2012) for the case of an M60 machine gun firing 7.62mm projectiles. From a qualitative standpoint, the best values that match the expected behavior for these distributions were found to be $\gamma = 800 \text{ s}^{-1}$ and $\delta = 1200 \text{ s}^{-1}$ and therefore these values are adopted in our simulations for the M2 HB Browning. Figure 3 shows the gas temperature profile and the internal heat transfer coefficient, respectively, at the selected position at 0.155 m from the breach during the first 6 ms after a round is fired. We notice that up to 1.46 ms the gas temperature at this specific location of the bore is essentially the ambient temperature of 303.15 K, and from this instant onwards the temperature is given by the internal ballistics results displayed on Table 3, ranging from 2,073.95 K at 1.46 ms until 1,674.45 K at 2.414 ms, when the projectile leaves the gun muzzle, and Eq. (8) becomes responsible for computing the temperature decay back to the ambient value. In a similar fashion, density and internal heat transfer coefficient start at 1.1614 kg/m³ and 10 kW/m²K, then range from 385.626 kg/m³ and 514,533.65 kW/m²K at 1.46 ms until 145.997 kg/m³ and 356,467.93 kW/m²K at 2.414 ms, respectively, and finally Eq. (9) is considered after this time instant.

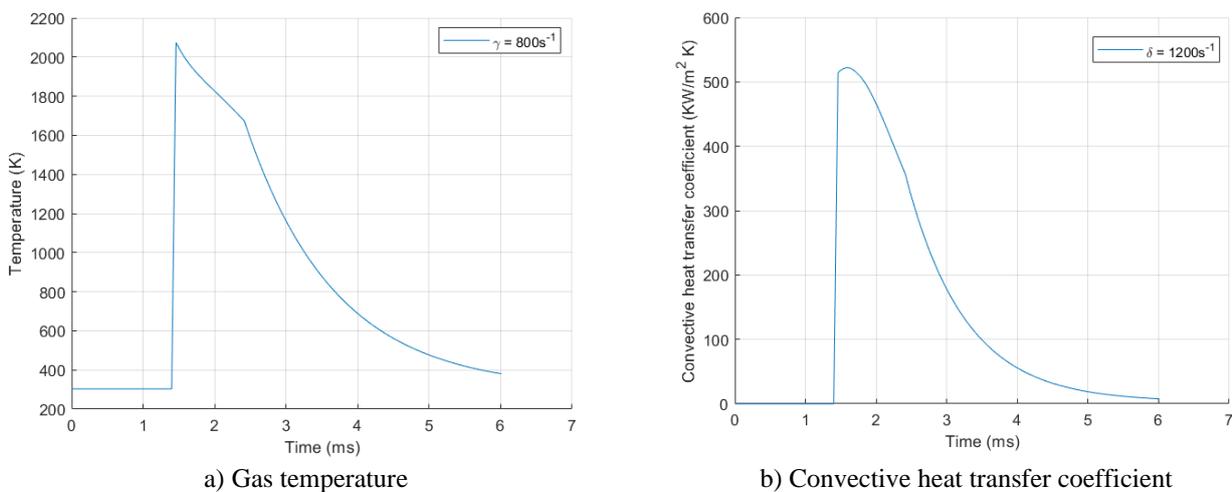


Figure 3. Gas temperature and internal heat transfer coefficient profiles at 0.155 m from the breach during the first 6 ms after a round is fired ($\gamma = 800 \text{ s}^{-1}$ and $\delta = 1200 \text{ s}^{-1}$)

Now, we are in a position to solve Equations 1 through 4 numerically. We employed the finite volume method implemented in the MATLAB® platform and the stability criterion for the solution was analyzed in order to furnish the

highest possible time step. Then, in order to assess the accuracy of the numerical approach in predicting the temperature distribution across the gun barrel, a thorough study was performed on the convergence behavior of the solution for different meshes. The best result was obtained for $\Delta r = 10^{-5}$ m.

3. RESULTS AND DISCUSSION

In this section, we explore some results obtained with the methodology described above. The accuracy of the single shot analysis is crucial for the simulations since any small deviation on the temperature assessment may cause significant error in the multiple shot analyses due to its accumulation behavior. Therefore, in accordance to the convergence and stability analysis performed, a mesh with $\Delta r = 10^{-5}$ m was selected in all our simulations to ensure convergent results. Figure 4 shows the numerical solution for the transient temperature distribution at the inner surface of the barrel under convective and radiative external cooling, and at 0.015 m from the breach as a function of time for the situation of a single shot. After the ammunition deflagration, a peak temperature of 991.20 K is attained at this specific location in approximately 1.4 ms, followed by a sharp reduction of the temperature due to the external cooling and hot propellant gas dissipation inside the bore. If a second round is not fired in sequence, then the barrel temperature will eventually return to the ambient value of 303.15 K. The same analysis was performed for the situation of constant thermal conductivity ($k = 35$ W/mK) and constant specific heat ($c_p = 600$ J/kgK) for the tube wall material in Eqs. (1) - (3), and the result is also shown in Figure 4. As it can be readily seen, a higher peak temperature of 1164.73 K is obtained for this simplified heat transfer model. This result suggests that an analysis performed with the hypothesis of constant thermophysical properties leads to overestimation of the gun inner wall temperature, thus being suitable for engineering purposes only, since it furnishes a conservative estimative for the cook-off temperature.

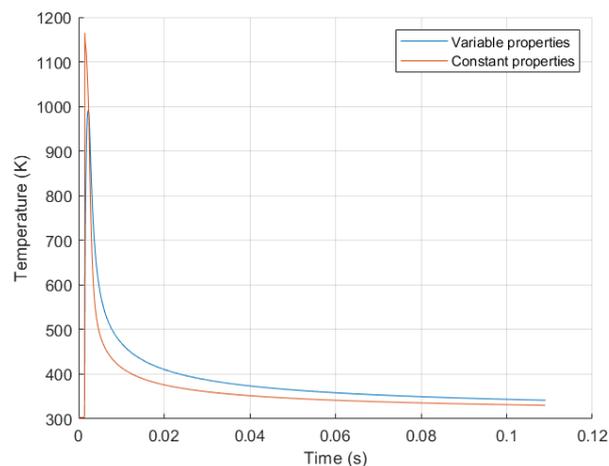


Figure 4. Temperature at the inner surface of the barrel at 0.1550 m from the breach of an M2 HB Browning machine gun as a function of time for one round

Figure 5 depicts the numerical solution for the transient temperature distribution of the inner surface of the barrel under convective and radiative external cooling, and for a 20 rounds burst at a firing rate of 550 rounds per minute, which results into a total firing time of 2.18 s. Clearly, a heating phase and a cooling phase can be observed at every round fired. The temperature at the end of each round, and consequently at the beginning of the next one, is represented by red dots in the figure. The temperature increment induced by every shot leads to an accumulated temperature that approaches the value of 446.17 K at the end of the burst. According to Akhavan (2004), nitrocellulose employed in modern firearms ammunition has a detonation temperature of approximately 453 K. On the other hand, Akçay and Yükselen (2014) reported a cook-off temperature of 488 K for 7.62 mm ammunition employed in a M60 machine gun. In the absence of cook-off temperature data for .50 ammunition in the archival literature, we shall adopt the value of 453 K as a safe limit. Therefore, for a continuous burst of 20 rounds, the cook-off temperature is not yet attained, although the result is close enough to raise concerns about the safety of the shooter due to the probability of self-detonation of the next rounds. In order to further investigate this matter, a new simulation was performed by considering a total of 130 rounds fired in 13 s. Figure 6 displays the temperature distribution at the inner surface of the barrel as a function of time computed with the values at the end of each round. Clearly, the limiting temperature of 453 K was attained before the end of the burst and thus this fire scheme might jeopardize the user's safety.

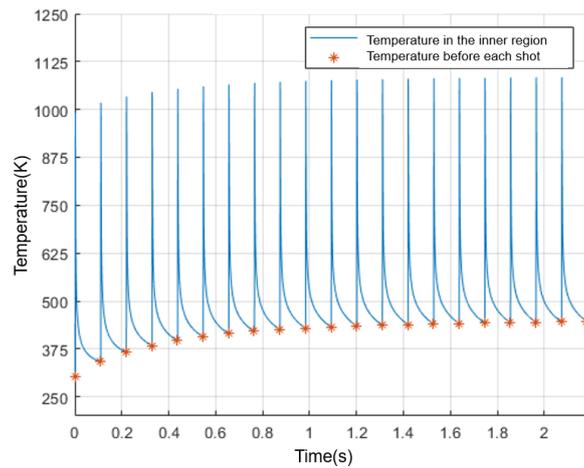


Figure 5. Temperature at the inner surface of the barrel at 0.1550 m from the breach of an M2 HB Browning machine gun as a function of time for a burst of 20 rounds

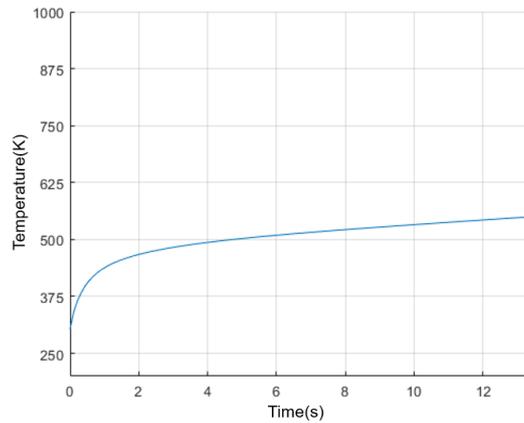


Figure 6. Temperature at the inner surface of the barrel at 0.1550 m from the breach of an M2 HB Browning machine gun as a function of time for a burst of 130 rounds

For continuous firing, the above results showed that the temperature rises rapidly at the inner surface of the machine gun barrel. Next, we performed simulations to assess the influence of a time interval between rounds and also the influence of consecutive bursts on temperature. For this purpose, we analyzed the situation of 30 rounds shot in different schemes such as: a continuous burst of 30 rounds, 2 bursts of 15 rounds, 3 bursts of 10 rounds, 6 bursts of 5 rounds, and finally 30 rounds fired intermittently.

Figure 7 summarizes the results obtained with these firing schemes. For sustained fire, as the number of rounds per burst decreases from 30 to 5, peak temperatures, as well as temperatures at the end of the sequence of rounds, decrease. Therefore, in order to prevent a possible cook-off temperature, it is better to shoot a total of 30 rounds in small bursts than in a single long burst. Also, shots in small bursts require less time between consecutive bursts to ensure lower temperatures at the beginning of the firing sequence. For intermittent fire, since there is not enough cooling time between rounds, the final temperature is higher than the ones attained with small bursts, but still lower than the one achieved with a long burst.

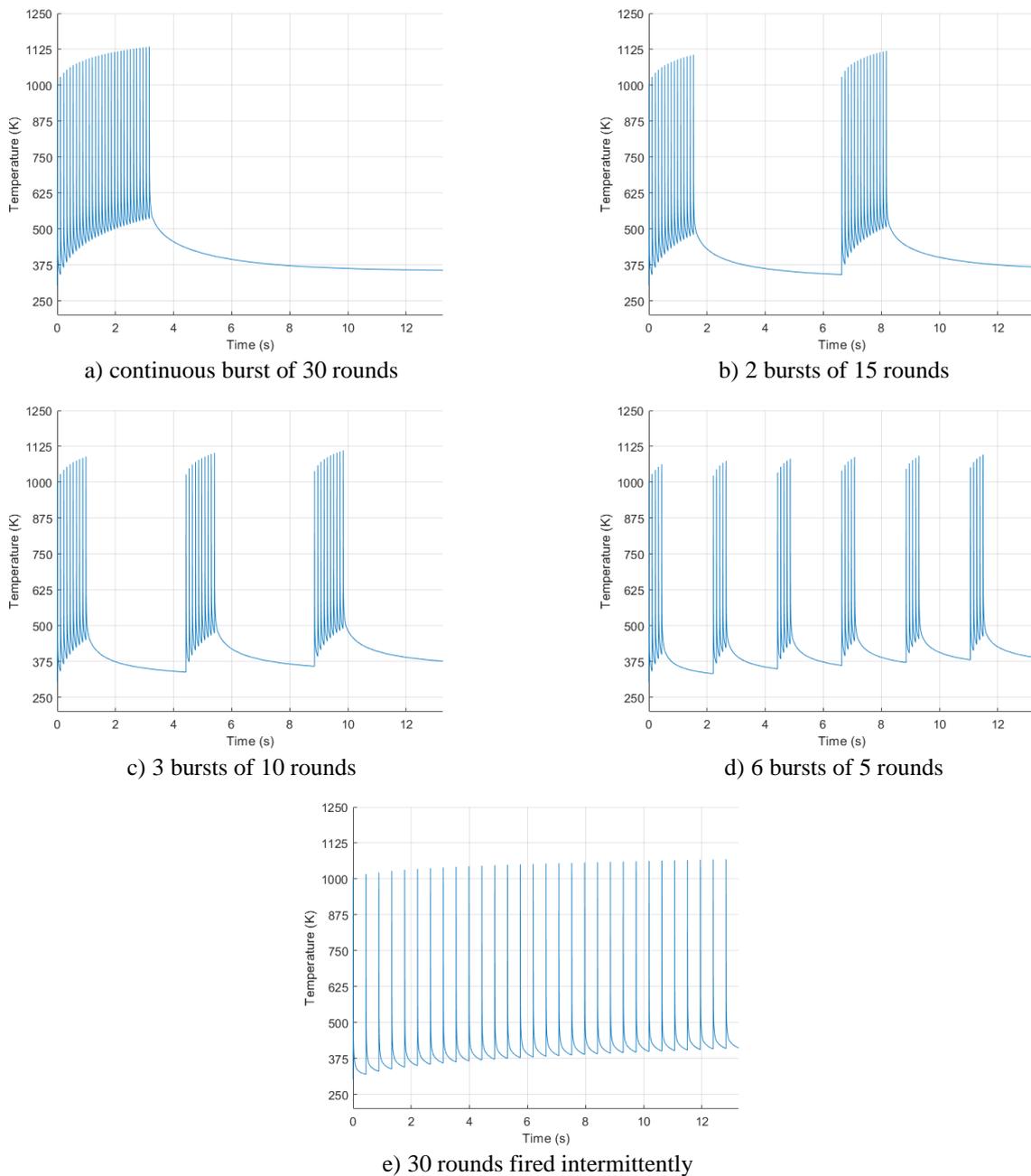


Figure 7. Temperature at the inner surface of the barrel at 0.1550 m from the breach of an M2 HB Browning machine gun as a function of time for several fire schemes.

4. CONCLUSIONS

We advanced a methodology suitable for the study of barrel temperature trends for various shooting schemes used by rapid-fire weapons, and a detailed analysis was performed for the M2 HB Browning .50 machine gun. Although the heat transfer phenomenon is more complex in real gun barrels, the advantage of the present one-dimensional model is to allow for simple, quick, but yet meaningful results for the prediction of possible cook-off temperatures. Alternative barrel geometries and materials can also be studied in a straightforward way by substituting for the temperature-dependent thermal properties and outer diameter at any position of interest along the barrel.

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