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COOK-OFF EVALUATION IN GUN BARRELS THROUGH A TRANSIENT HEAT TRANSFER ANALYSIS

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Abstract. *Gun designers have long realized that during repeated firing situations, a great amount of heat is transferred to the inner surface of the barrel due to the burning of the propellant. As the firing sequence continues, the thermal load increases despite the natural heat loss through the outer wall of the gun barrel and consequently, the bore of the weapon experiences an acute temperature elevation as the ballistic cycle takes place. In gun operations at moderate and high rates, the time between rounds is probably insufficient for the dissipation of the thermal load to the environment and therefore a management of firearms involving passive or active cooling methods is commonly utilized. However, even when such strategies are employed, a critical event is expected to arise where the safety of the operating crew, the accuracy of the projectile and the life span of the gun barrel are seriously compromised. This undesirable outcome is known as the "thermally induced firing" or the "cook-off condition". In this circumstance, an uncontrolled and unexpected detonation of the ammunition is achieved due to the elevated temperatures in the gun chamber caused by previous firing rounds. Therefore, the main purpose of this contribution is to perform a numerical analysis of the transient temperature distribution in gun barrels when operating in burst mode. An effective model based on the heat diffusion equation in cylindrical coordinates is advanced where an imposed heat flux boundary condition in the inner wall accounts for various types of charges and manufacturing arrangements. On the other hand, the outer boundary condition deals with heat dissipation by means of a simultaneous convection and linearized radiation process. The mathematical formulation of the problem is addressed by the finite volume method and care was taken to verify this solution against analytical results published in the open literature for both a single and multiple rounds. The results obtained so far indicate that the number of safe rounds of firing before the attainment of the cook-off condition is significantly dependent of the inner flux boundary condition associated to the ammunition.*

Keywords: *Transient thermal analysis, gun barrels, "cook-off" condition, finite volume method.*

1. INTRODUCTION

Armed forces around the world routinely perform artillery rounds in a rapid sequence. For this kind of combat mission, the knowledge of the heat flow rates to the inner surface of the gun is a key factor for devising passive or active cooling gun barrel strategies in order to prevent high bore temperatures. Depending on the number of rounds fired per minute, the chamber surface temperature could reach an undesirable condition known as the cook-off temperature of the propellant. In this circumstance, an uncontrolled and unexpected detonation of the loaded ammunition is achieved due to the elevated temperatures in the gun chamber caused by previously fired rounds, jeopardizing the safety of the gun crew. Moreover, large amounts of heat wear and erode the gun bore thus reducing the accuracy of the projectile and ultimately diminishing the life span of the barrel. In order to circumvent this problem, large-caliber weapons subjected to long-burst firing, such as guns and howitzers, must be cooled. Therefore, the main purpose of this contribution is to perform a numerical analysis of the transient temperature distribution in gun barrels when operating in sustained fire. For this purpose, some expressions for the inner wall heat flux in guns that are commonly employed in the literature are here utilized and critically compared. The influence of possible inaccuracies in the manufacturing process of the propellant that could lead to distinct liberation of heat is also analyzed.

2. LITERATURE REVIEW

A brief literature review indicates that the heating of gun barrels during sequences of fire have received a fairly amount of attention over the years with special emphasis to the prediction of cook-off temperatures in different scenarios. Suyadnya *et al.* (2019) explored the performance of a gun barrel by employing a mathematical model based on the one-dimensional heat diffusion equation, admitting that the outer wall is subjected to a natural convective cooling and also allowing for radiation effects which are later found to be negligible. A convective heat transfer process between the bore surface and the hot gas propellant allows for the determination of the inner boundary condition. By means of a finite volume scheme, they evaluated the transient temperature history of a 155 mm caliber gun for various situations. Their results indicate that 27 rounds of fire can be safely discharged until a cook-off temperature of 180 ˚C is attained.

Mishra *et al.* (2010) utilized the ANSYS finite element package to simulate another one-dimensional transient temperature distribution of a 155 mm gun barrel subjected to artillery rounds different of those described in the above paragraph. An interesting aspect of this particular contribution is that the inner boundary condition is now taken as a prescribed heat flux which rapidly decays over time in an exponential fashion. Moreover, main focus is given to the evaluation of the initial and maximum bore temperatures for each cycle of fire. Their main conclusion is that the model here advanced produced accurate results when compared with experimental temperature data. This, in turn, suggests that the exponential inner heat flux is a good approximation to the complex set of phenomena that occurs in the inner surface of a gun during cycles of fire.

Akçay and Yulkselen (2014) also utilized a one dimensional transient heat transfer analysis to predict the temperature history of a 7.62 mm M60 machine gun barrel. Here, both the thermal conductivity and the specific heat are supposed to be temperature dependent. In addition, a convective heat transfer process in the inner wall is assumed to occur. Accordingly, the gas temperature and the convective heat transfer coefficient are evaluated by taking into account some inner ballistics aspects of ammunition. The simulations concluded that a cook-off temperature of 215 ˚C is attained after a 130 rounds of firing, which quite close to what is observed in experimental setups of such machine guns.

Hameed *et al.* (2014) reported in a detailed monograph, the design of an apparatus which aims at simulating the gun barrel and cartridge behavior in an actual cook-off situation. More specifically, the purpose of the experiment is to determine the possible times at which cook-off reaction may occur. This is performed by evaluating the upper and lower temperature limits of each temperature range where the cook-off phenomenon was noticed. They employed a 7.62 mm caliber cartridge and their results indicated that below the 146 ˚C threshold for the barrel temperature, cook-off is very unlikely to develop. A further investigation in their data, reveal that the propellant utilized in the experiments yields cook-off effects for barrel temperatures of about 152 ˚C with the reaction occurring less than 300s after round chambering.

Evi and Işik (2018) conducted a series of ballistic experiments in agreement with NATO standards for a 7.62x51mm ammunition where the tests allowed for single and multiple firing. The temperature distribution is evaluated by the heat diffusion equation where the inner boundary condition is of the third type. Moreover, the gas heat transfer coefficient was calculated as a function of both the Reynolds and Prandtl numbers. Also, thermodynamic properties were computed according to the gas mixture law. An interesting feature of this research is that stress components over the axial, radial and circumferential directions are evaluated through a generalized Hooke's Law that involves the thermal expansion coefficient of the barrel. Tests were carried out over a wide range of temperatures in which the double-base propellant was conditioned. Pressure distributions along the barrel and bore temperatures are displayed for a variety of climatic conditions. Furthermore, outer surface temperatures evaluated from a numerical analysis are critically and successfully compared with thermal imaging results for a 20 shot firing sequence. Among other aspects, their research concluded that an increase of the initial propellant temperature leads to higher temperatures and pressures in the barrel which in turn increases the stress of the material.

As mission requirements of foreseeable combat missions call for large caliber guns that have high-energy propellants, passive cooling technologies such as chromium plating are no longer effective. Consequently, a whole new set of the so-called "active cooling technologies" for gun barrels are currently under development. Wu *et al.* (2008) explored the effects of a full length midwall-cooling scheme in a monobloc 155 mm gun barrel. The mathematical model is once again based on the one-dimensional transient heat transfer problem with appropriate boundary conditions to simulate the energy exchange between the barrel and the cooling channels. An exponentially decaying heat flux is utilized to model the inner boundary condition and temperature profiles are obtained by means of a commercial package that utilizes a finite element analysis. One of the most intriguing conclusions of their research is that the forced liquid cooling strategy significantly enhances the thermal dissipation rate and therefore the gun is able to deliver more bursts of fire without attaining the cook-off temperature. Beltran *et al.* (2012) also studied the temperature distribution in gun barrels with midwall-cooling effects, but were able to deliver a fully analytical solution to the heat transfer problem based on eigenfunction expansion techniques.

3. PHYSICAL PROBLEM AND MATHEMATICAL FORMULATION

In this section, we present the mathematical formulation of the transient temperature field of a gun barrel upon a sequence of rounds which is being cooled at its outer surface by a mixed linearized convection-radiation process, with a heat transfer coefficient h_∞ and environment temperature T_∞. The gun barrel is modeled under a transient one-dimensional, temperature-independent property situation as a hollow cylinder of inner and outer radius given by r_i and r_o, as shown in Figure 1, with an initial uniform temperature T_0.

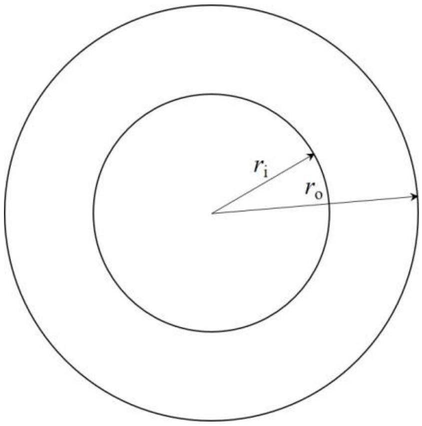


Figure 1. Schematic of domain geometry.

The inner surface of the gun receives a transient heat flux *q(t)* from the hot propellant gases that propagates along the gun bore after the ammunition deflagration. Accordingly, the mathematical formulation for this heat diffusion problem is given by:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r}\frac{\partial T}{\partial r} + k\frac{\partial^2 T}{\partial r^2} \qquad r_i < r < r_o \qquad t > 0 \tag{1}$$

$$T = T_0 \qquad r_i \le r \le r_o \qquad t = 0 \tag{2}$$

$$-k\frac{\partial T}{\partial r} = q(t) \qquad r = r_i \qquad t > 0 \tag{3}$$

$$k\frac{\partial T}{\partial r} + h_\infty T = h_\infty T_\infty \qquad r = r_o \qquad t > 0 \tag{4}$$

As discussed in the previous section, the heat flux from the hot propellant gases typically presents an exponential behavior in time and can be modeled by considering distinct mathematical approximations. The most common approximation (Wu *et al.*, 2008) is the simple exponential distribution showed in Eq. (5) that has one parameter "b" associated to the rate of decay. In this form, only the decrease in energy after the projectile is fired is considered. On the other hand, in order to incorporate in the model the increase of energy due to the hot gases, the Laplace distribution, known as double exponential, may be alternatively used as presented in Eq. (6). This equation has two parameters, one parameter associated to the location (α) and one scale parameter (β). In addition to these two approximations, a previous work (Jablonski and Jablonski, 2017), employed the Weibull distribution to describe the heat flux in gun barrels. In this distribution, given by Eq. (7), one parameter is associated to the scale (λ) and the other one to the shape (η). In this contribution, Eq. (5) through (7) will be used to model the inner heat flux from the hot propellant gases.

$$q(t) = q_0 \exp(-bt) \tag{5}$$

$$q(t) = q_0 \frac{1}{2\beta} \exp\left(-\frac{|t-\alpha|}{\beta}\right) \tag{6}$$

$$q(t) = q_0 \frac{\eta}{\lambda}\left(\frac{t}{\lambda}\right)^{\eta-1} \exp\left[-\left(\frac{t}{\lambda}\right)^{\eta}\right] \tag{7}$$

Having completed the problem formulation, we now seek a numerical solution based on the finite volumes method for the determination of the transient temperature distribution of the gun barrel during and after the first round.

4. VERIFICATION OF THE NUMERICAL SOLUTION

The finite volume numerical solution here obtained was verified by means of an analytical approach available in the literature (Beltran *et al.*, 2012) that employs the exponential heat flux formulation described by Eq. (5). After this verification stage, different shapes of heat flux were investigated in order to assess if the cook-off temperature might be attained. In addition, in order to encompass distinct ammunition manufactures, a variation of 0.8 and of 1.20 in the standard values for the predicated energy released by the propellant was also investigated.

In the analytical solution presented by Beltran *et al.* (2012), Eqs. (1) – (4) as applied to a 155 mm compound gun barrel were solved through the eigenfunction expansion method. Their heat flux formulation utilized the values of q_0 = 192.7 MW/m² and b = 210.97 s^{-1}. In order to address the same mathematical problem in this present research, the finite volume method was applied to Eq. (1) with a mesh of 15,000 finites volumes and a time step of 0.01 ms. Data presented in Table 1 were considered for the numerical verification phase.

Table 1. Parameters and thermophysical properties of the gun barrel (Wu *et al.*, 2008).

Parameters	Value	Unit
Thermal Conductivity, k	40	W/(m.K)
Specific heat, c_p	460	J/(kg.K)
Density, ρ	7833	kg/m³
Heat transfer coefficient, h_∞	40	W/(m².K)
External temperature, T_∞	27	°C
Initial temperature, T_0	27	°C
Inner radius, r_i	77.5	mm
Outer radius, r_o	107.5	mm

The comparison between the analytical and numerical solution are presented in Figure 2 for a single round, and in Figure 3 for burst fire. From an engineering point of view, the discrepancies among the solutions are considered to be negligible for both the inner and outer surfaces. Therefore at this point, both the numerical code and the numerical solution are considered to be verified.

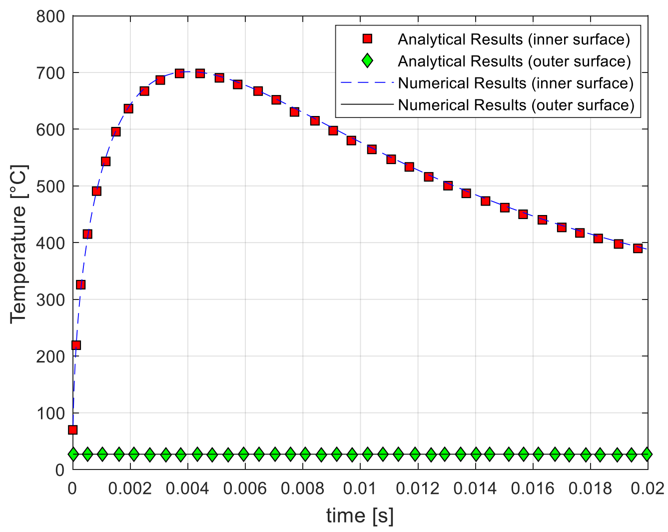


Figure 2. Inner and outer surface temperature comparisons between the analytical and numerical solution for a single round.

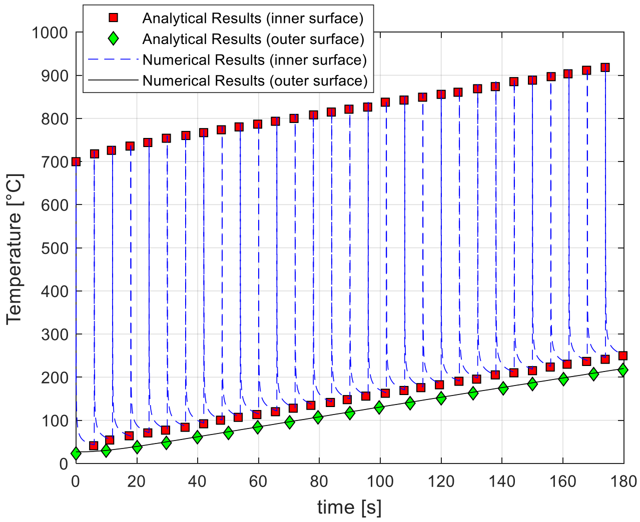


Figure 3. Inner and outer surface temperature comparisons between the analytical and numerical solutions for sustained fire considering that one round is fired every 6 s.

5. RESULTS AND DISCUSSION

The numerical solution for a 155 mm howitzer using the thermal properties in Table 2 was obtained for different forms of heat flux considering the formulations presented in Eq. (5) through Eq. (7). Weibull distribution heat flux formulation adopted by Jablonski and Jablonski (2017) was used as a reference and is labelled here as a standard situation. The parameters used in this particular form are presented in Table 3 together with others heat flux parameters. Additionally, a possible variation in the energy liberated by the propellant was also investigated. Different cases, showed in Table 4 were analyzed in order to study the influence of this parameter in the cook-off condition.

Table 2. Parameters used for a 155 mm howitzer gun barrel (Jablonski and Jablonski, 2017).

Parameters	Value	Unit
Thermal Conductivity, k	50	W/(m.K)
Specific heat, c_p	470	J/(kg.K)
Density, ρ	7800	kg/m³
Heat transfer coefficient, h_∞	28	W/(m².K)
External temperature, T_∞	27	°C
Initial temperature, T_0	27	°C
Inner radius, r_i	77.5	mm
Outer radius, r_o	101	mm

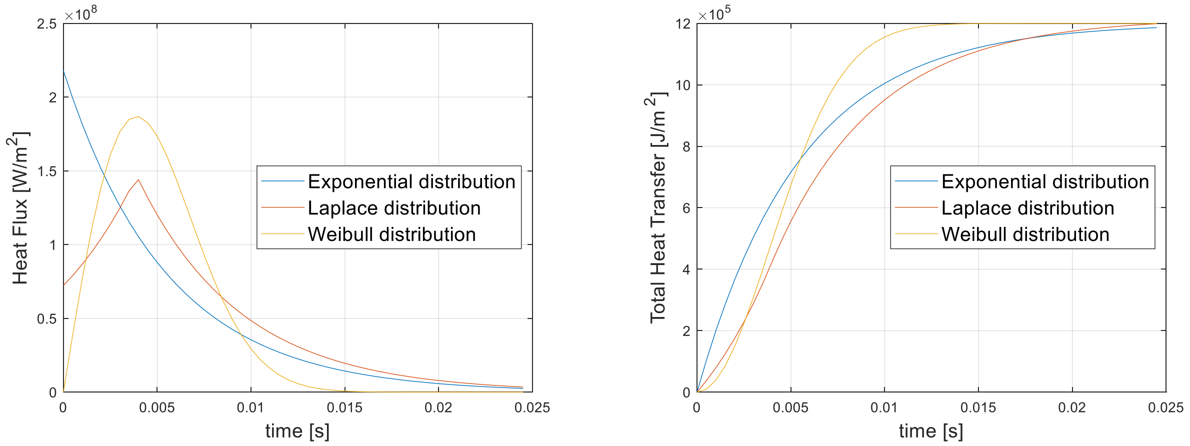
Table 3. Heat flux parameters.

Parameters	Values
b	0.0055
α	0.0039
β (s)	0.0055
λ (s)	0.0055
η	2

Table 4. Set cases under investigation.

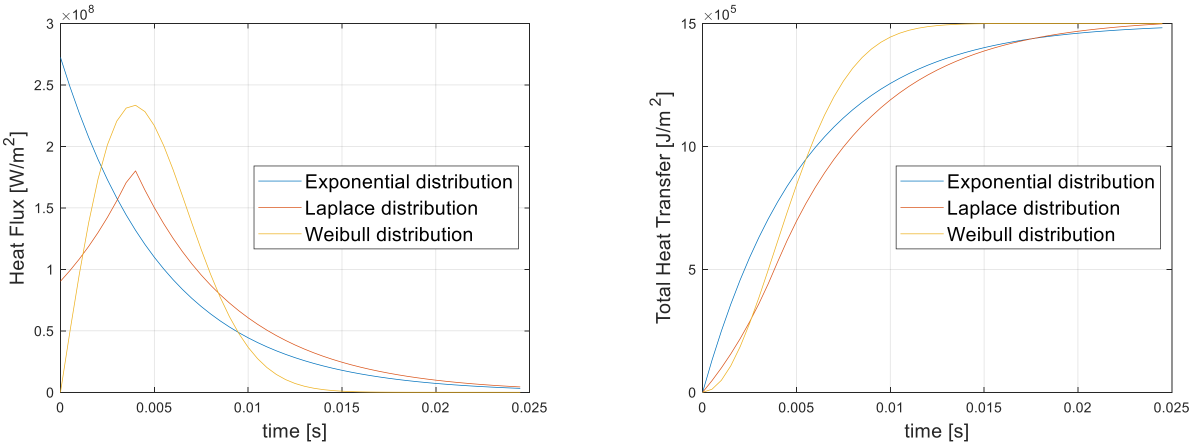
Cases	q_0 [MW/m^2]
1	216
2	270
3	324

The form for each heat flux condition together with the total heat liberated by the propellant are illustrated in Figures 4 to 6 for the cases presented in Table 4.



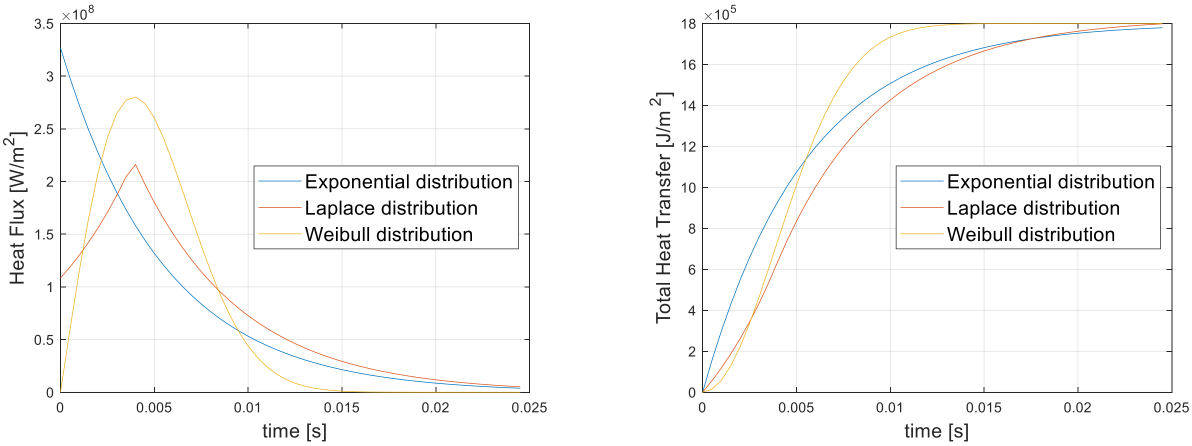
a) Heat Flux b) Total Heat Transfer

Figure 4. Heat flux and heat transfer for the case 1 situation.



a) Heat Flux b) Total Heat Transfer

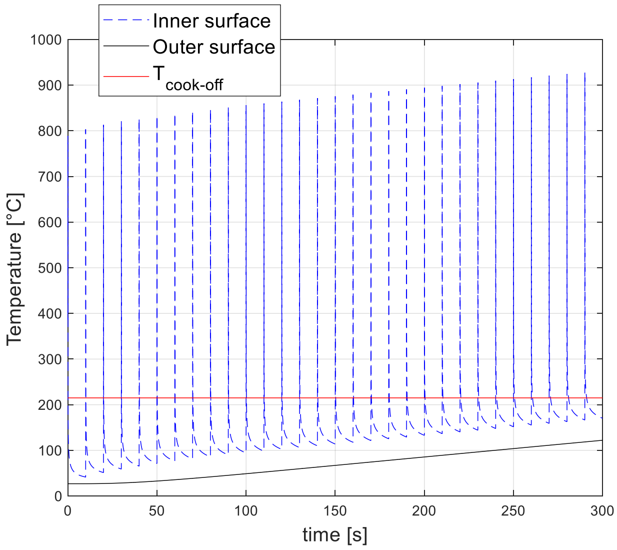
Figure 5. Heat flux and heat transfer for the case 2 situation.



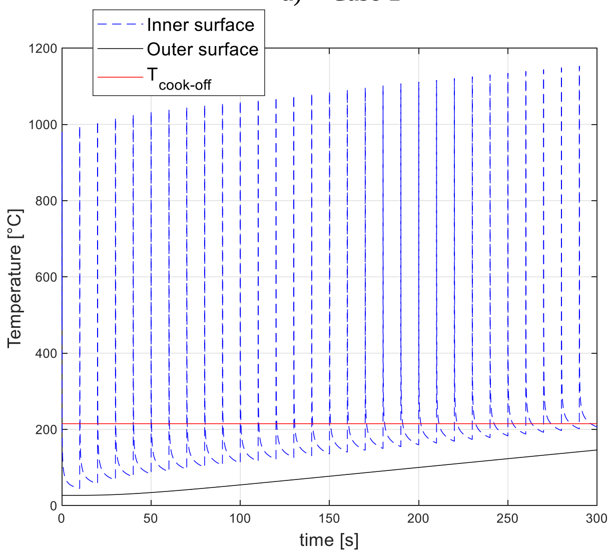
a) Heat Flux b) Total Heat Transfer

Figure 6. Heat flux and heat transfer for the case 3 situation.

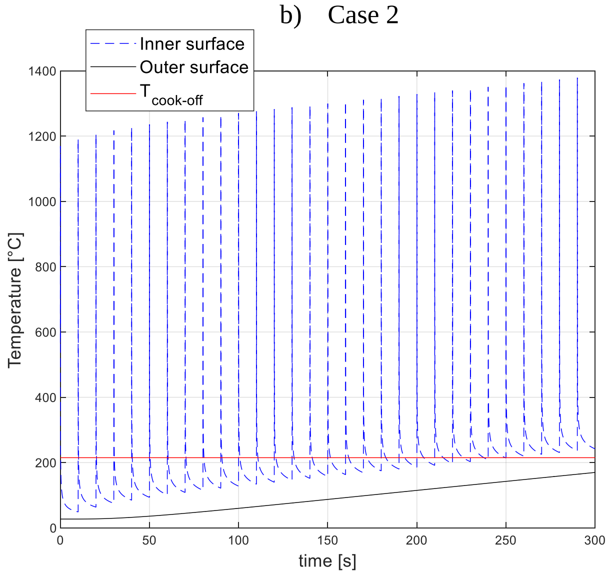
The numerical solution for the temperature in the inner and outer surfaces of the gun barrel was obtained for 30 rounds with a 10 s interval between the rounds. The evolution of the temperature surfaces is presented in Figures 7, 8 and 9 for the heat flux proposed in Eq. (5), Eq. (6) and Eq. (7), respectively.



a) Case 1

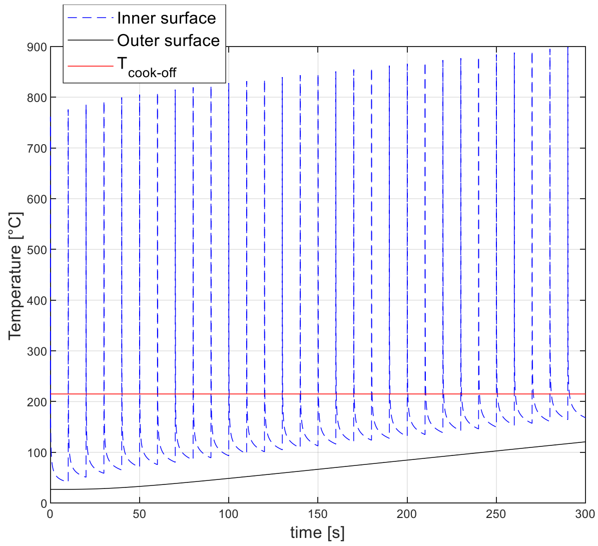


b) Case 2

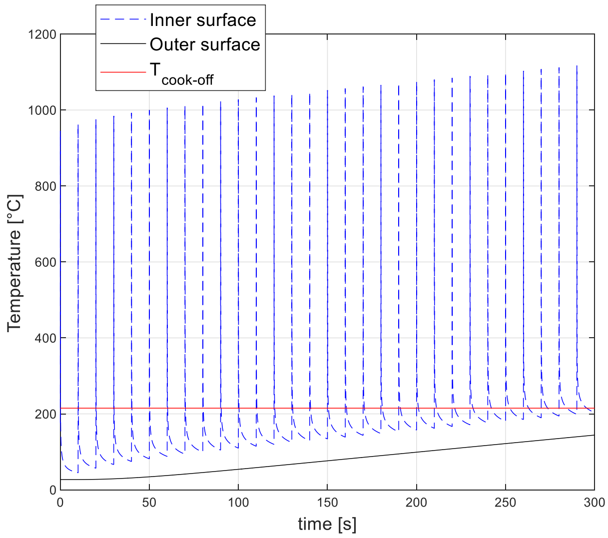


c) Case 3

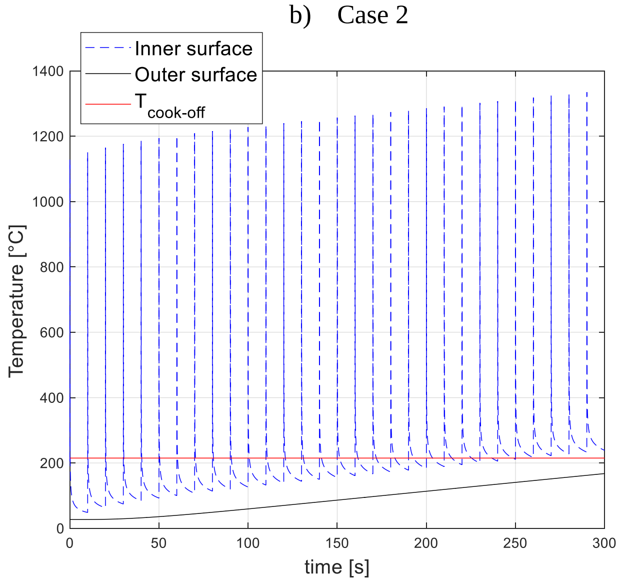
Figure 7. Inner and outer surfaces temperatures for the heat flux of Eq. 5.



a) Case 1

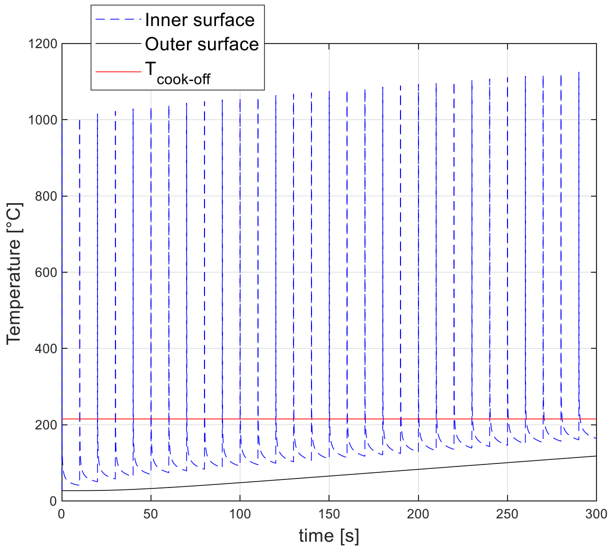


b) Case 2

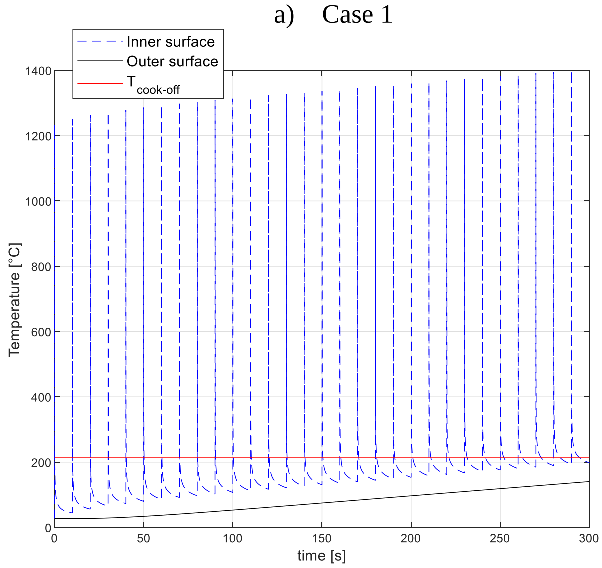


c) Case 3

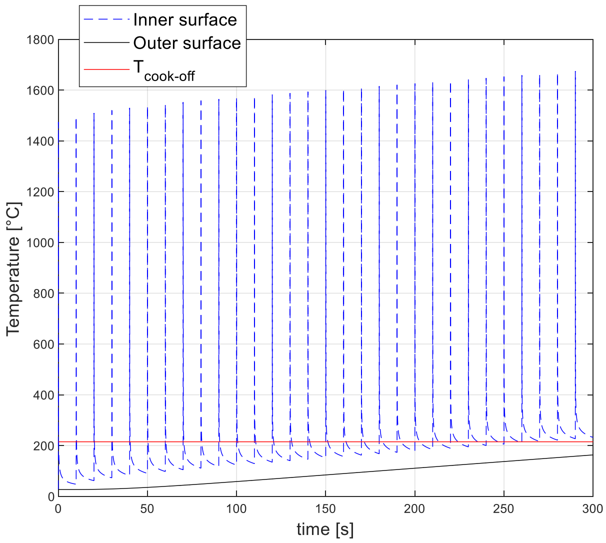
Figure 8. Inner and outer surfaces temperatures for the heat flux of Eq. 6.



a) Case 1



b) Case 2



c) Case 3

Figure 9. Inner and outer surfaces temperatures for the heat flux of Eq. 7.

An inspection of these results reveals some interesting trends. For example, let us consider a temperature of 215 °C which is commonly employed for the evaluation of the cook-off condition. Figures 6 and 7 indicate that the thermally induced fire is not attained and therefore, the operating crew can safely perform the execution of the 30 round burst as originally planned. However, if the energy liberated by the propellant follows the case 3 scenario, the cook-off condition is reached at the end of the 26th detonation for the case of the exponential and Laplace heat flux formulations or at the 27th round if the Weibull distribution is a good representation of the inner heat flux boundary condition.

In conclusion, this research advanced a simple yet reliable numerical method for the determination of the transient temperature distribution in gun barrels subjected to a natural outer convective cooling. In addition, the interior ballistic problem is here modelled as three different types of a prescribed heat flux, in accordance with previous contributions found in the archival literature. The simulations carried out so far indicate that the parameter q_0 which represents the rate of energy release at the onset of the detonation, in correspondence with Eq. (5), appears to be the main variable influencing the number of rounds until the cook-off condition is reached. Consequently, experiments aimed at evaluating this parameter are to be conducted with proper care and precision.

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