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NUMERICAL THERMAL ANALYSIS OF AN 81MM MORTAR

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Abstract: *Light-weight infantry supporting weapons are designed for neutralization of manpower and firing positions in an open field battle scenario. In this type of device, a grenade is expelled causing an increase in the temperature of the weapon barrel. During repeated firing situations, a large amount of heat is transferred to the inner surface of the mortar barrel due to the burning of the propellant. As the firing sequence continues, the thermal load increases in spite of the natural loss of heat through the outer wall of the tube and, consequently, the inner surface of the barrel experiences a sharp rise in temperature as the ballistic cycle continues. An undesirable effect of this heating process is related to a potential inaccuracy of the trajectory of the projectile. Therefore, the main purpose of this contribution is to perform a numerical analysis of the transient temperature distribution in an 81 mm light mortar, which is one of the most common types of mortar employed in the battlefield in rapid firing sequences. The heat diffusion equation is solved by using the finite difference method applied to a cylindrical geometry. Several heat flux distributions are tested in order to investigate the effect on the thermal behavior of the weapon. The numerical code was verified by comparing the present results with a previously published analytical solution for both a single round and a sequence of rounds fired by a 155mm gun. The results obtained so far indicate that high temperatures are reached for certain rates of fire sequences which may lead to a thermally induced self-ignition situation. This undesirable condition may endanger the safety of the operating crew or render the weapon ineffective for combat.*

Keywords: *81mm mortar, heat flux, numerical analysis, finite difference method, gun tube heating.*

1. INTRODUCTION

Nowadays, modern combat demands a well-organized military structure with accuracy to deliver indirect fires. Therefore, all the supporting mortar units need to be focused on timely sustainable fire sequences on an open field battle scenario. The firing process occurs when a grenade is ejected from the mortar, which increases the temperature of the weapon barrel. Due to the burning of the propellant during repeated firing, a large amount of heat is transferred to the inner surface of the barrel. For this type of military operation, it is critical to understand and predict the heat flow rates at the inner surface of a weapon tube in order to avoid elevated bore temperatures. Moreover, the inner surface temperature could achieve an undesirable level which is known as the cook-off temperature depending on the conditions of a long-sustained firing scheme. Thus, the main purpose of this contribution is to perform a numerical analysis of the transient temperature distribution in an 81 mm light mortar, which is one of the most used artillery pieces that operate in rapid firing sequences. Accordingly, some typical heat flux distributions are imposed on the inner surface of the tube in order to investigate their role on the mortar thermal behavior.

2. LITERATURE REVIEW

Wu et al. (2008) focused on heat transfer in a 155 mm midwall cooled compound gun barrel and in a 155 mm natural air cooling monobloc gun barrel studying implications with barrel liquid-cooling method. In this work, the finite element numerical method was utilized in order to validate the theoretical results and also to understand the heat transfer process in a long firing sequence with a decreasing heat flux exponential function in the inner surface of the

gun barrel. The results showed the inefficiency of natural convection with the objective to transfer the heat out of the barrel due to the small combination of the convection and radiation heat transfer coefficients. Therefore, forced liquid cooling was chosen as the best method for improving the thermal dissipation rate and maintaining the chamber temperature below the cook-off temperature by increasing the heat transfer coefficient. Moreover, the simulation under natural convection condition reached the cook-off temperature when performing 43 rounds with one round being fired every 6s for a 3 min firing sequence. Also, an optimum flow rate was discussed and could be used to balance the cooling channels because of the relationship between the optimum heat transfer coefficient and the temperature difference.

Lawton (2001) employed the equation of mass diffusion to generate a simple Arrhenius equation in order to connect the wear caused by each round fired with the initial temperature, the gun bore temperature and propellant erosion in chemical zones affected by the burning of hot gas. This phenomenon is better understood by analyzing the thickness of this region. These correlations are verified by vessel tests with an examination of the gun wear rates from various weapon barrels, considering that the theory is limited to normal wear at the commencement of rifling. This work noted that the cause of gun barrel erosion was related to high temperatures occurring at the commencement of rifling when the gun firing process happens. This high temperature actually enables the diffusion of chemical components from propellant gas on the surface of weapons, even for a few milliseconds.

Beltran et al. (2012) conducts a theoretical approach in a one-dimensional heat transfer 155 mm gun barrel performing an analytical solution in order to determinate the transient temperature profile when subject to convective cooling at the walls. Different cases were presented regarding the external convective cooling with natural air, forced liquid cooling and midwall cooling channels for multiples rounds fired.

Mishra et al. (2010) used the computational software ANSYS 11 to simulate a one-dimensional 155 mm howitzer with a finite element method as the numerical model in order to predict the transient temperature history in the gun barrel. The exponentially decaying heat flux form was used as a boundary condition at the gun bore surface. The number of rounds required to reach the charge related to cook-off temperature was investigated for a particular type of ammunition. One of their findings indicates that wear or erosion is sensitive during the process of firing the weapon and is associated to the peak temperature on the surface of the barrel.

Suyadnya et al. (2019) developed a mathematical model based on the one-dimensional heat diffusion equation, considering that the inner boundary condition was determined by a convective heat transfer mechanism between the bore surface and the hot gas propellant. In addition, the outer surface experiences a natural convective cooling coupled with radiation effects. In repeated firing situations, a 10 s cooling interval between the rounds is imposed. The computational simulation was performed using finite elements, and the numerical results were validated using experimental data from Mishra et al. (2010), which are related to a cooled 155 mm gun bore. One of their main conclusions is that the radiation effect does not play a significant role in the cooling process and that 27 firing rounds can safely be executed prior to reaching a 180°C cook-off temperature at about 294 seconds.

3. PHYSICAL PROBLEM AND MATHEMATICAL FORMULATION

This section describes the mathematical formulation for the transient one-dimensional heat diffusion in the barrel of a mortar, for certain firing conditions. Initially, the barrel is considered to be in thermal equilibrium with the outer ambient air at temperature T_∞ . As the firing sequence evolves, the inner surface of the weapon tube experiences a transient heat flux, $q(t)$, from the burning of the propellant that, in turn, causes an increase in the temperature of the gun barrel. During this process, the mortar is cooled by natural convection with the ambient air and therefore an external heat transfer coefficient h_∞ and outer temperature T_∞ are needed for the formulation. By establishing the geometry of the mortar barrel as a hollow cylinder of inner and outer radius R_{in} and R_{ext} , it is a simple matter to derive the equations for the transient temperature field as:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial T}{\partial r} + k \frac{\partial^2 T}{\partial r^2} \quad R_{in} < r < R_{ext} \quad t > 0 \quad (1)$$

$$T = T_0 \quad R_{in} \leq r \leq R_{ext} \quad t = 0 \quad (2)$$

$$-k \frac{\partial T}{\partial r} = q(t) \quad r = R_{in} \quad t > 0 \quad (3)$$

$$k \frac{\partial T}{\partial r} + h_\infty T = h_\infty T_\infty \quad r = R_{ext} \quad t > 0 \quad (4)$$

The representation of the inner heat flux is critical for the accurate determination of the temperature field during the barrel heating due to the firing of multiple rounds. As a result, several investigations are presented in the literature aiming at different heat flux distributions in gun barrels in order to better understand the thermal behavior of the weapon. A careful analysis of the contributions of Wu et al. (2008), Lawton (2001) and Mishra et al. (2010) indicates that the heat flux from the hot propellant gases may be properly described by means of an exponentially decaying function that may assume some distinct forms. One of such patterns is the classical exponential distribution which is represented in Eq. (5) where the parameter “b” allows for the establishment of the rate of decay. Moreover, Jablonski and Jablonski (2017) and Telles et al. (2021) reported a Weibull heat flux distribution in gun barrels that may represent more involved thermal behaviors as described by Eq. (6). Here, a scale parameter (λ) and also a shape constant variable (η) are needed in order to establish a particular flux form.

$$q(t) = q_{01} \exp(-bt) \quad (5)$$

$$q(t) = q_{02} \frac{\eta}{\lambda} \left(\frac{t}{\lambda}\right)^{\eta-1} \exp\left[-\left(\frac{t}{\lambda}\right)^\eta\right] \quad (6)$$

4. NUMERICAL ANALYSYS

The set of equations (1) to (6) were discretized by means of an implicit finite difference scheme (Ozisik et al., 2017) and implemented in the MATLAB[®] environment. Some details of the hardware equipment utilized in the present research are described in Table 1.

Table 1. Computational system specifications for the present simulations.

System	Core	RAM	Bits
Microsoft Windows 10 Pro	Intel i5 6400 2.70Ghz	16 GB	64

4.1 Verification of the numerical solution

The finite difference numerical solution was verified by establishing a comparison between the present results and a previously research report, Beltran et al. (2012), that proposed an analytical approach for a single round situation and established an external cooling by natural convection. Also, a sequence of 30 rounds fired by a 155 mm howitzer was simulated. In both studies, the same one-dimensional heat flow model is adopted as to simulate the transient temperature field and the exponential heat flux formulation, described in Eq. (5), parameter b is set to 210.97 s^{-1} together with an initial heat flux of magnitude $q_{01} = 192.7 \text{ MW/m}^2$. Here, the thickness of the wall is considered to be 30 mm and the barrel is supposed to be manufactured from special steel which is typically used in weaponry. Table 2 describes the parameters and thermophysical properties employed in the verification phase.

Table 2. Thermophysical properties and parameters of the 155 mm howitzer.

Parameters	Value	Unit
Thermal conductivity, k	40	W/(m.K)
Specific heat, c_p	460	J/(kg.K)
Density, ρ	7833	kg/m ³
Heat transfer coefficient, h_∞	40	W/(m ² .K)
External temperature, T_∞	27	°C
Initial temperature, T_0	27	°C
Inner radius, R_{in}	77.5	mm
Outer radius, R_{ext}	107.5	mm

Accordingly, the heating period for one round is defined to be 0.02 s while the cooling period is determined as 5.98 s in order to assume that one round is fired every 6 s. In addition, the firing sequence lasts for 3 min with at a rate of 10 rounds per minute. In the numerical simulations, the time step for a single round and for a sequence of rounds have a magnitude of 0.1 ms. Figures 1 and 2 displays a comparison of the present evaluations with previously published results for a single round and 3 minutes mission of fire. An analysis of these results indicates an excellent agreement for both the inner and outer surfaces of the gun. Therefore, the numerical code and the numerical solution are considered to be validated.

Additionally, some interesting physical trends can be observed from both Fig. 1 and Fig. 2. In the case of a single shot, the inner surface reaches a maximum bore temperature of 700.73 °C in 4.07 ms during the heating phase, followed by a rapid decline, while the outer temperature of the barrel remains practically unchanged. However, when 30 rounds are fired, the surface temperature experiences a gradual rise from 27 °C up to approximately 220 °C at 180 s. This behavior is due to the fact that as the firing sequence advances, more heat is released from the burnt propellant as it gradually diffuses along the barrel thus increasing its temperature. In order to further discuss this aspect, Tables 3 and 4 explore the overall performance of the present numerical scheme with the analytical results from Beltran et al. (2012).

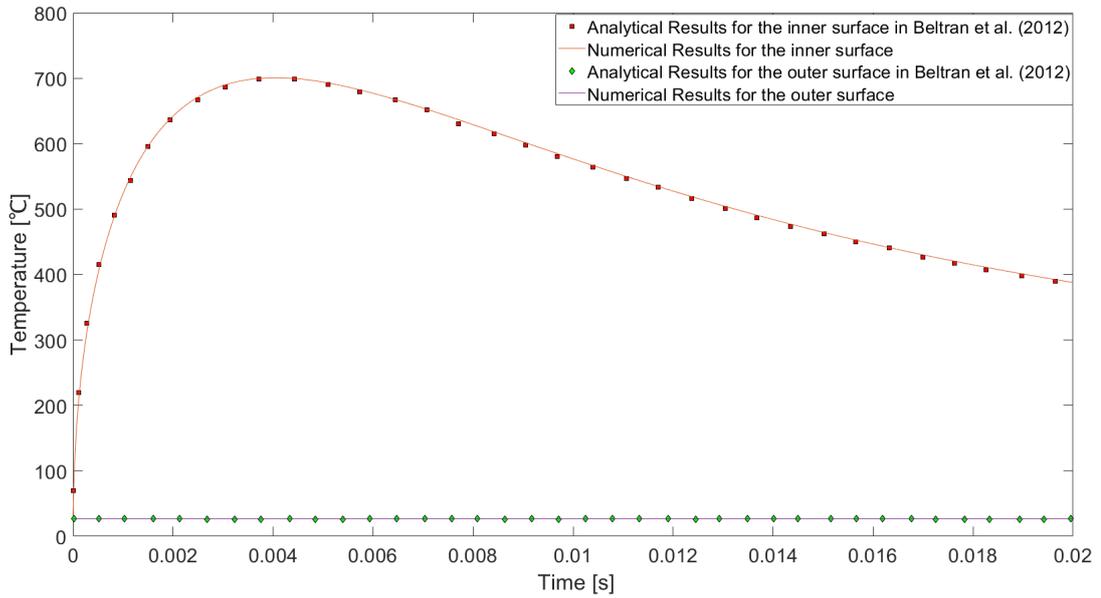


Figure 1. Comparison between the numerical and the analytical solutions for a single round.

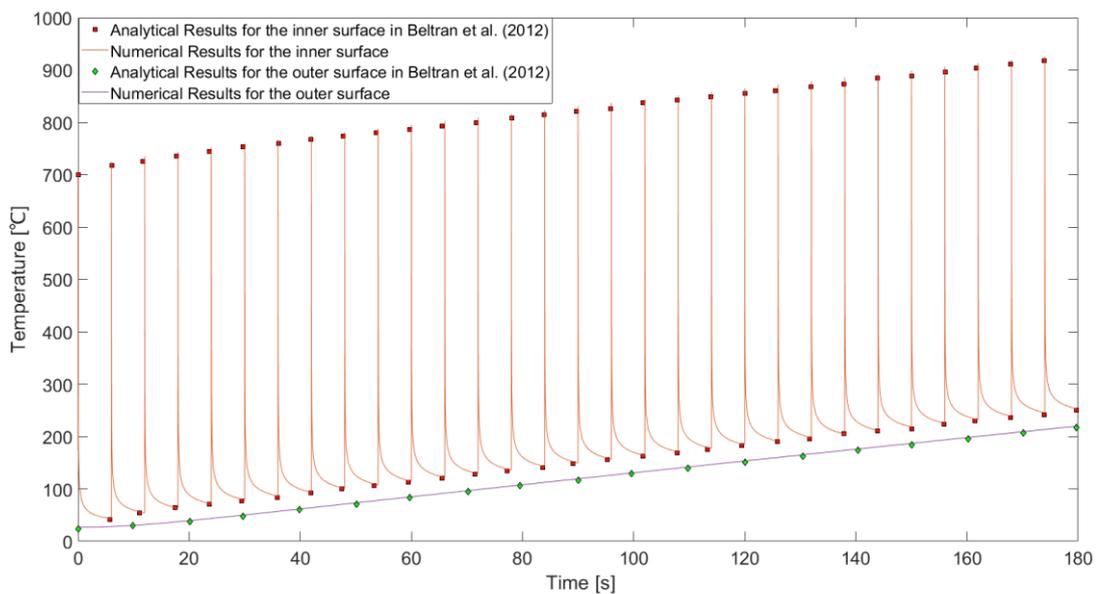


Figure 2. Comparison between the numerical and the analytical solutions for a sequence of rounds.

Table 3. Comparison between the numerical and the analytical solutions at the outer radius temperature with 30 rounds fired.

Time (s)	Analytical results for the surface temperature (°C)	Numerical results for the surface temperature (°C)	Relative Error (%)
1	27.00	27.00	0.00
6	28.00	28.03	0.11
10	29.70	30.25	1.85
20	37.83	39.48	4.36
30	47.67	50.39	5.71
40	60.92	61.75	1.36
50	70.75	73.52	3.92
60	83.81	85.05	1.48
80	106.89	108.03	1.07
90	116.73	119.44	2.32
100	129.78	130.77	0.76
120	151.16	153.46	1.52
140	174.05	175.95	1.09
150	184.08	187.19	1.69
160	195.43	198.05	1.34
180	216.81	220.21	1.57

Table 4. Comparison between the numerical results of bore surface temperature with previously published results in 155mm gun barrel.

Round No.	Initial bore surface temperature Beltran et al. (2012) (°C)	Numerical results of the initial bore temperature (°C)	Relative error (%)	Maximum bore surface temperature Beltran et al. (2012) (°C)	Numerical results of the maximum bore temperature (°C)	Relative Error (%)
1	41.05	43.19	5.21	717.80	723.98	0.86
2	54.29	54.28	0.01	725.94	735.11	1.26
3	64.13	63.29	1.30	735.77	743.70	1.07
4	70.75	71.33	0.82	744.10	752.16	1.08
5	77.19	78.89	2.20	753.94	759.59	0.74
6	83.81	86.21	2.86	760.37	767.00	0.87
7	91.94	93.42	2.15	766.99	774.25	0.94
8	100.27	100.55	0.28	773.61	781.25	0.98
9	106.89	107.65	0.71	780.24	788.48	1.05
10	113.32	114.71	1.22	786.67	795.27	1.09
11	119.95	121.75	1.50	793.29	802.58	1.17
12	128.08	128.77	0.54	799.91	809.33	1.17
14	141.32	142.76	1.02	814.67	823.59	1.09
16	156.08	156.67	0.38	826.21	837.46	1.36
18	169.14	170.51	0.81	842.48	851.07	1.01
20	182.38	184.28	1.04	855.95	865.11	1.07
22	195.43	197.98	1.30	868.78	878.39	1.10
24	210.19	211.61	0.67	885.24	892.44	0.81
26	223.43	225.17	0.77	896.78	905.30	0.95
28	236.49	238.67	0.92	911.54	919.07	0.82
30	249.73	252.09	0.94	918.16	925.79	0.83

Table 3 studies the transient temperature field for the outer surface of the weapon when cooled by a natural convection process while Table 4 investigates the magnitudes of lower and upper bounds of temperature for each of the 30 round firing sequence. On general terms, an excellent agreement is found as a maximum deviation of about 6% is observed upon inspection of the tables.

5. RESULTS AND DISCUSSION

After the verification phase, two distinct heat flux distributions were investigated in order to predict the thermal behavior of the 81 mm mortar barrel, indicated in Fig. 3a. The total heat transfer released by the propellant is investigated in Fig. 3b.

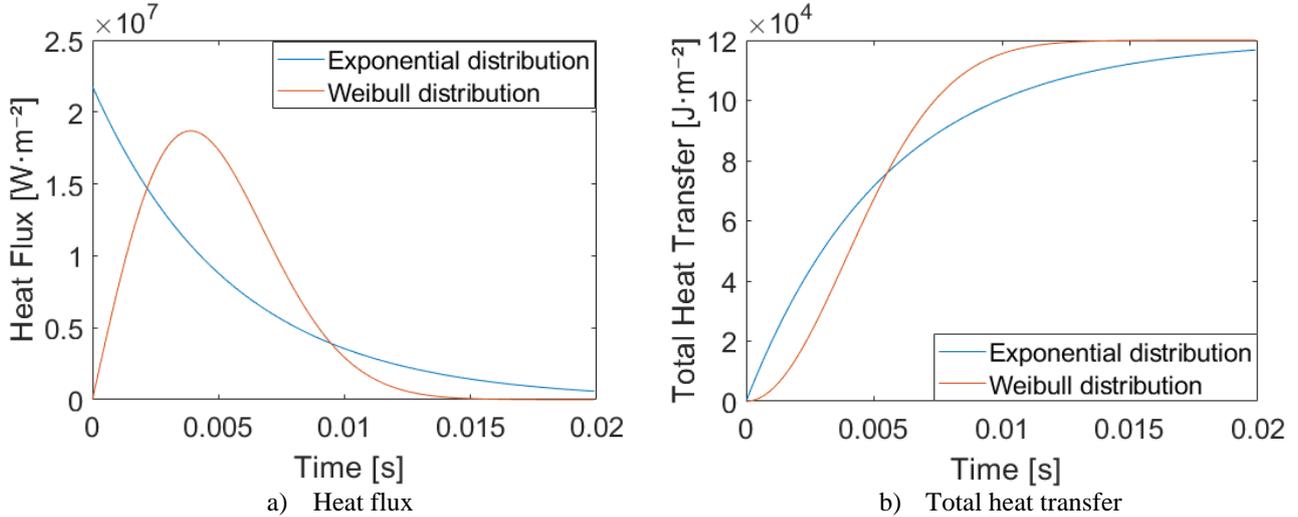


Figure 3. Heat flux and total heat transfer released by the propellant.

The thermophysical properties utilized in this particular case are shown in Table 5. Table 6 exhibits the various parameters that are needed in the simulations related to the use of Eqs. (5) and (6).

Table 5. Thermophysical properties and parameters of the 81mm mortar.

Parameters	Value	Unit
Thermal conductivity, k	50	W/(m.K)
Specific heat, c_p	470	J/(kg.K)
Density, ρ	7800	kg/m ³
Heat transfer coefficient, h_∞	28	W/(m ² .K)
External temperature, T_∞	27	°C
Initial temperature, T_0	27	°C
Inner radius, R_{in}	40.5	mm
Outer radius, R_{ext}	47.5	mm

Table 6. Heat flux parameters.

Parameters	Value	Unit
b	0.0055	s ⁻¹
λ	0.0055	-
η	2	-
q_{01}	21.79	MW/m ²
q_{02}	0.12	MW/m ²

Also, the heating period of a single round is taken to be the same as in the verification phase and is set to be 0.02 s with a computational domain of $\Delta r = 4.67 \mu\text{m}$ and $\Delta t = 0.10 \text{ ms}$. Moreover, a total of 30 rounds were simulated with a 10 s interval between rounds. Figures 4 to 7 investigated several numerical results for the temperature in the inner and outer surfaces in order to predict the thermal behavior of the 81 mm mortar barrel.

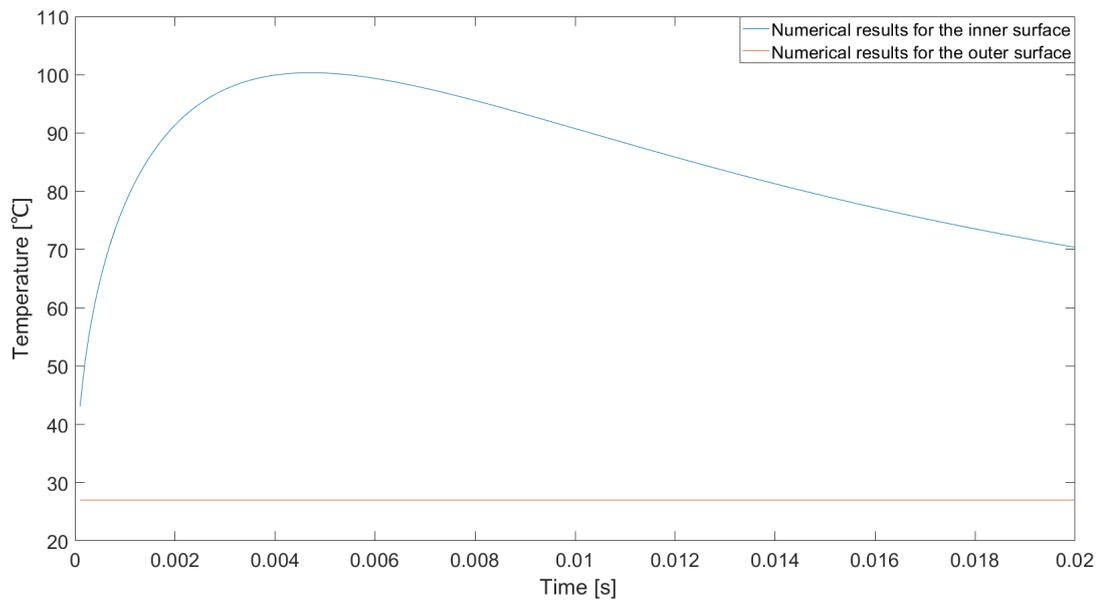


Figure 4. Numerical results for the temperature in the inner and outer surfaces of the 81 mm mortar for an exponential heat flux distribution and a single round.

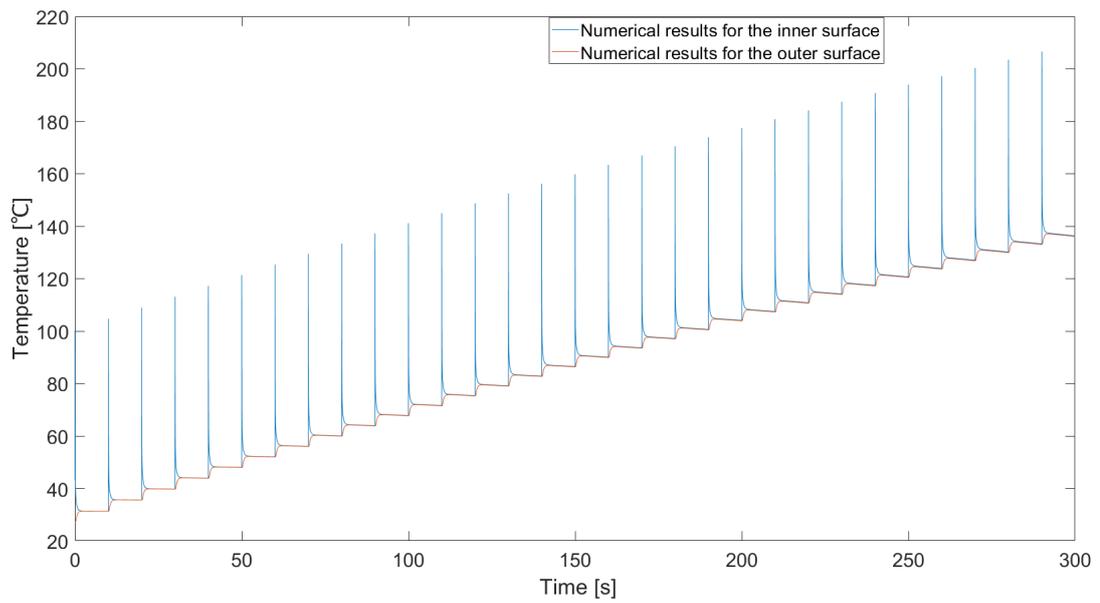


Figure 5. Numerical results for the temperature in the inner and outer surfaces of the 81 mm mortar for an exponential heat flux distribution and 30 rounds.

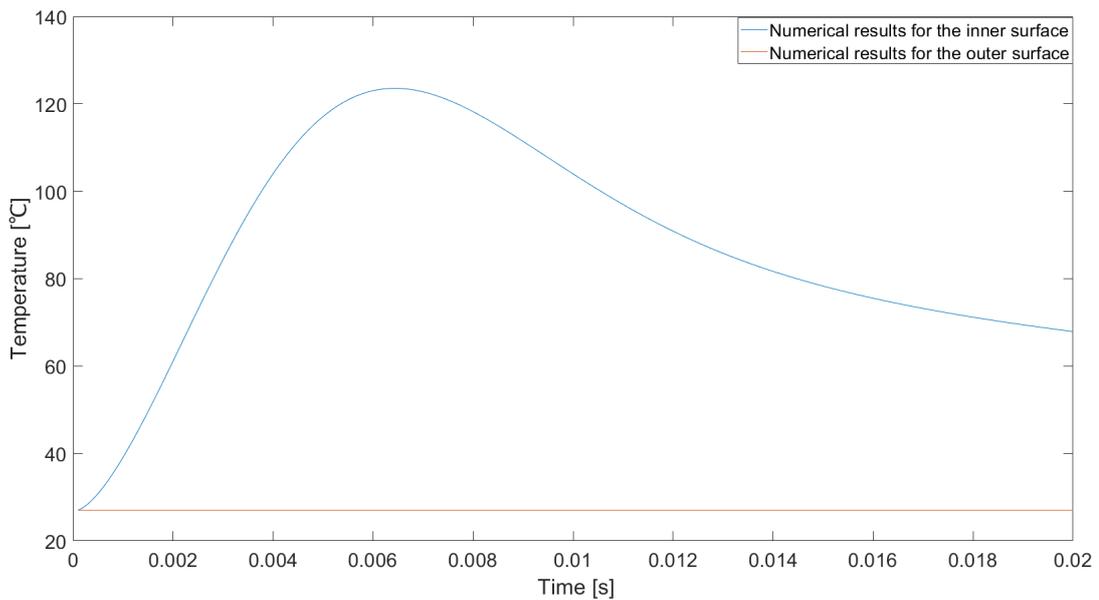


Figure 6. Numerical results for the temperature in the inner and outer surfaces of the 81 mm mortar for a Weibull heat flux distribution and a single round.

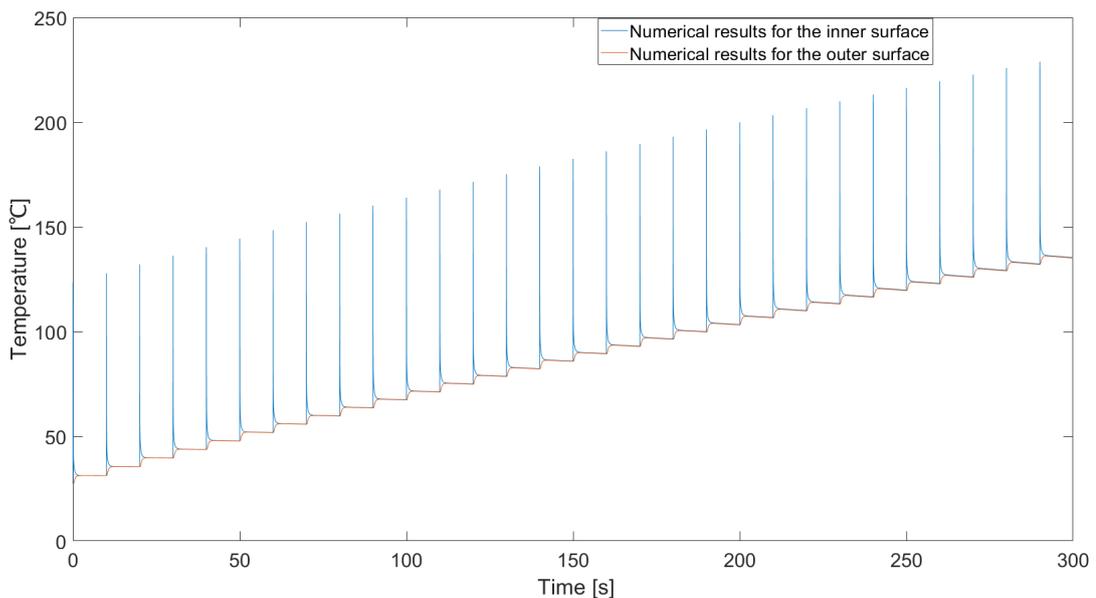


Figure 7. Numerical results for the temperature in the inner and outer surfaces of the 81 mm mortar for a Weibull heat flux distribution and 30 rounds.

An inspection of Figs. 4 to 7 discloses some striking features of the mortar thermal behavior that is somewhat similar to those already discussed in the previous section. The form of the inner heat flux does not appear to have a significant role in the outer temperature distribution for a single round as it remains essentially that of the initial condition. This fact suggests that a “semi-infinite” formulation approach may furnish acceptable results if one is interested only in the thermal characteristics of a single round. When a sequence of 30 rounds is simulated, both distributions associated to Eqs. 5 and 6 produce the same overall effect. For example, in the case of Weibull distribution, if a temperature of 200 °C is taken to be the threshold of the thermally induced detonation for the 81 mm mortar, the safety of the operating crew may be compromised after the 22nd sequence as from this point onwards, the bore inner temperatures are consistently above this level.

In order to assess the influence of a possible variation of the q_0 parameter in the thermal behavior of the mortar barrel, some selected scenarios are now investigated and presented in Tab. 7. A reduction from 1 to 0.7 together with an

increase of 1 to 1.5 in the standard magnitude of q_0 was imposed leading to the various heat flux temporal distributions of Fig. 8.

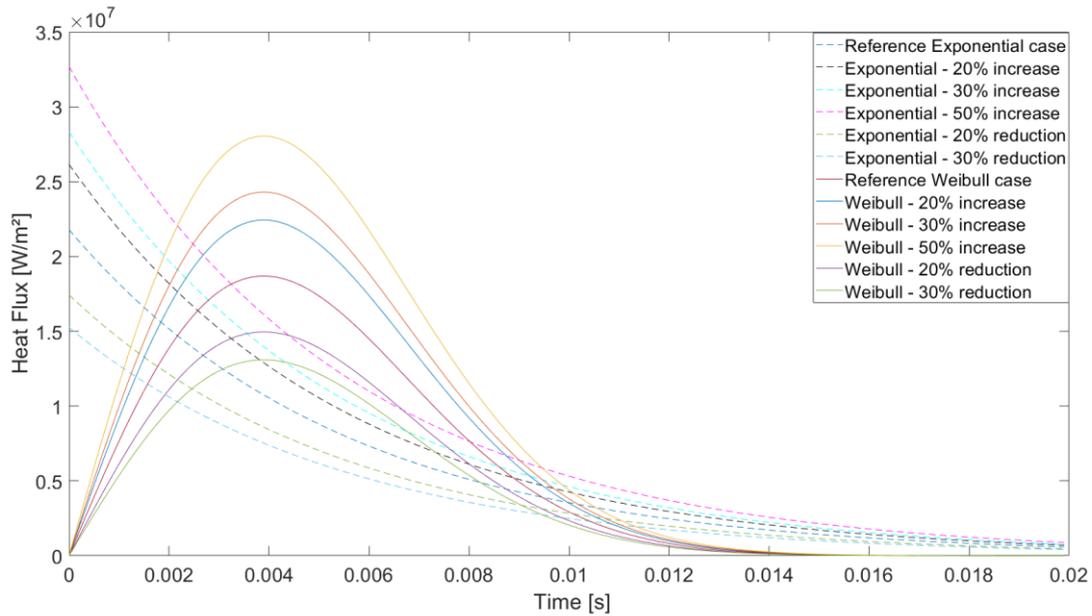


Figure 8. Selected heat flux distributions.

Table 7. Comparison between several heat flux distributions for the initial bore and surface temperature for the case of a single round and for the 30th round.

Heat Flux	Temperature (°C) R_{in} (single round $t = 0.02$ s)	Temperature (°C) R_{in} (single round $t = 10$ s)	Peak temperature (°C) R_{in} (30 th round)	Temperature (°C) R_{ext} (single round $t = 0.02$ s)	Temperature (°C) R_{ext} (single round $t = 10$ s)	Peak temperature (°C) R_{ext} (30 th round)
Exponential Standard (Eq. 5)	70.39	31.65	221.70	27.00	31.64	145.42
Exponential 20% increase	79.07	32.59	260.64	27.00	32.57	168.85
Exponential 30% increase	83.40	33.05	280.11	27.00	33.04	180.67
Exponential 50% increase	92.08	33.98	319.05	27.00	33.97	204.31
Exponential 20% reduction	61.71	30.72	182.76	27.00	30.71	121.56
Exponential 30% reduction	57.37	30.26	163.29	27.00	30.25	109.74
Weibull Standard (Eq. 6)	67.89	31.23	228.00	27.00	31.22	134.50
Weibull 20% increase	76.07	32.08	268.20	27.00	32.07	156.00
Weibull 30% increase	80.16	32.50	288.30	27.00	32.49	166.73
Weibull 50% increase	88.34	33.35	328.50	27.00	33.34	188.25
Weibull 20% reduction	59.71	30.38	187.83	27.00	30.38	113.00
Weibull 30% reduction	55.62	29.96	167.70	27.00	29.95	102.25

Table 7 displays the temperature in both the inner and outer surfaces of the mortar for the selected variations in the q_0 parameter. Results are collected for a single round at 0.02 s (duration of the internal ballistic cycle), at the end of a 10 s interval (duration of the charge sequence), and for the peak temperature of the bore and outer surfaces during the 30th round. Here, a marked difference is observed regarding the effective magnitude of the q_0 parameter. As already mentioned before, either a decaying exponential or a Weibull distribution yields practically the same values for the lower bound temperatures in the inner region of the gun barrel for the case of a single round. On the other hand, for a fixed shape of the inner heat flux, a variation of the effective magnitude of q_0 produces a temperature difference of 9 °C for the two heat flux profiles with a 50% increase. Also noticeable is the fact that the 200°C limit for a possible self-ignition is only observed in the cases associated to a reduction in the standard heat flux magnitude, for the sequence of 30 rounds. Moreover, it is interesting to acknowledge the magnitudes of the outer surface temperatures for the 30 round sequence. If the operating crew handles the mortar immediately at the end of this particular round sequence, they risk a severe burn injury, as temperatures markedly above the “safe to touch” figure is observed.

In conclusion, the present contribution presented a model together with a numerical simulation of the transient temperature field of an 81 mm mortar subjected to two typical inner heat fluxes related to the interior ballistics of such weapon for both the cases of a single and multiple rounds. The numerical scheme was successfully verified with an analytical solution reported in the open literature. A series of tabulated results for the inner and outer temperatures are produced and investigated vis-a-vis with a possible “cook-off” and burning injuries situations. Our current research efforts are now focused on the evaluation of the inner heat flux through inverse problems techniques.

6. ACKNOWLEDGEMENTS

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