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Analysis of Heat Transfer in a 35 mm Barrel of an Anti-Aircraft Cannon

Andrzej DĘBSKI, Piotr KONIORCZYK, Zbigniew LECIEJEWSKI*,
Marek PREISKORN, Zbigniew SURMA, Janusz ZMYWACZYK

Military University of Technology, Faculty of Mechatronics and Aerospace,
2 Sylwestra Kaliskiego Street, 00-908 Warsaw, Poland
Corresponding author's e-mail address: zbigniew.leciejewski@wat.edu.pl

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Abstract. The paper presents the results of computer simulations of unidentified transient heat transfer in the wall of a 35 mm cannon barrel for a single shot and for a sequence of seven shots with a subsequent firing break. The cannon barrel was made of 32CrMoV12-28 steel. For the phenomenon modelling, it was assumed that the material of the barrel wall is uniform and the barrel's inner surface does not feature a protective coating of galvanic chrome or a nitrided casing. Calculations were performed for two input data variants: (i) for constant values of thermophysical parameters and (ii) for a temperature-dependent specific heat. The barrel with an overall length of 3150 mm was divided into 6 zones. On the inner surface of the barrel in each zone there were assumed various values of heat flux density expressed as rectangular functions $\dot{q}_i(t, r_w, z) = const_i$ in the range from 0 to 10 ms (with the start of t_i of the function $\dot{q}_i$ shifted in the subsequent zones). The calculation time for a single shot was assumed as equal to 100 ms. The calculations were performed with a finite element method in COSMOS/M software.
Keywords: mechanics, heat transfer, anti-aircraft cannon barrel

1. INTRODUCTION

Anti-aircraft artillery systems usually comprise several cannons, where some of them fire at a designated target, while remaining cannons track the target without firing. This is caused by the firing timing for a single cannon selected to prevent high temperatures occurring in the barrel from firing. When the barrel of one of the cannons overheats, the firing of that cannon is paused. The firing is then switched to the cannons which are tracking the target in stand-by. It is also possible to fire all cannons of the battery simultaneously. When developing a firing cycle during service life testing of cannon barrels it is critical to keep the temperature below the maximum value of 800ºC as established by the manufacturer [1, 3]. The maximum temperature limit of the barrel bore in operation is imposed by the characteristics of the barrel's steel grade. In the steel grade contemplated, temperatures above 800ºC result in allotropic transformations related to the reconstruction of the alloy crystal lattice. The transformations are endothermic during the temperature rise and, in their first stage, take the heat from the barrel bore which is concomitant with a negative change of volume within the transformation zone. The kinetics of the transformations are well described by dilatometric curves characteristic of specific steel grades. The temperature effect on the barrel bore changes the volume of the superficial layer, resulting in a typical grid of cracks. This contributes to the peeling of the protective coating on the barrel's inner surface. The protective coating is made of galvanic chromium, applied in older manufacturing processes, or a nitrided casing in newer designs. In both cases, the protective coating is eroded by the structural transformations within the base material which are related to the phase transition between ferrite and austenite. Currently, research is being conducted on implementing novel steel grades with a higher allotropic transition temperature [4] in cannon barrel production.

This means that a firing cycle must be applied which includes firing stages and predefined firing breaks. The heat transfer calculation methods defined in the reference literature are often too time-consuming to be applied for a firing cycle of several hundred shots. The paper presents the calculation of heat transfer in an anti-aircraft cannon, calibre 35 mm, overall barrel length 3150 mm. It was assumed that the material of the barrel wall is uniform and the barrel's inner surface does not feature a protective coating of galvanic chrome layer or a nitrided casing.

An initial boundary value problem was solved for the single shot, i.e. a heat conduction equation with an initial condition and boundary conditions. The calculation was reiterated for a sequence of seven shots with a subsequent firing break. The calculations are performed relatively fast on a PC workstation. The proposed heat transfer model can be easily fine-tuned to experimental data, and the calculations are possible for large numbers of shots.

The heat transfer of a 35 mm anti-aircraft cannon barrel contemplated herein (i.e. a barrel without an inner protective coating) was already a subject of analysis and solution of the so-called internal ballistic main problem [2]. Based on the calculation results for the relation of the heat flux density on the barrel's inner surface $\dot{q}_{\mathrm{Pi}}(t,r_w,z)$ at 6 cross-sections designated P1: $z = 216$ mm, P2: $z = 385$ mm, P3: $z = 535$mm, P4: $z = 880$ mm, P5: $z = 2081$ mm, P6: $z = 2980$ mm, $\dot{q}_{\mathrm{Pi}} = \dot{q}_i(t,r_w,z)$ was assumed in the 6 zones along the barrel's inner surface length, see Fig. 1 (the legend of Fig. 1 also features the barrel's outer diameter values r_z in the specific zones, from S1 to S6). Next, the functions $\dot{q}_i(t,r_w,z)$ were approximated as rectangular functions $\dot{q}_i(t,r_w,z) = const_i$ in a range from 0 to 10 ms (with the shift of the start t_i of $\dot{q}_i$ in the subsequent zones S1 to S6: $t_1 = 0$ ms, $t_2 = 1.76$ ms, $t_3 = 2.06$ ms, $t_4 = 2.5$ ms, $t_5 = 3.59$ ms, $t_6 = 4.25$ ms), see Fig. 2 [2].

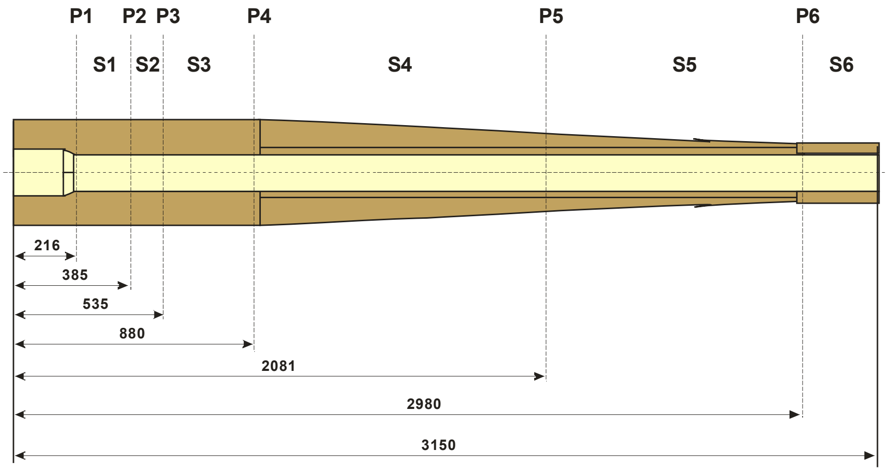

Fig. 1. Heat transfer zones S1 to S6 of the 35 mm cannon barrel input to the calculations:
S1: 0 to 385 mm, $r_z = 55.0 \div 55.0$ mm; S2: 385 to 535 mm, $r_z = 55.0 \div 57.0$ mm;
S3: 535 to 880 mm, $r_z = 57.0 \div 59.5$ mm; S4: 880 to 2081 mm, $r_z = 59.5 \div 44.07$ mm;
S5: 2081 to 2980 mm, $r_z = 44.07 \div 31.0$ mm; S6: 2980 to 3150 mm, $r_z = 31.0$ mm [2]

The calculations assume constant heat flux density values $\dot{q}_i(t,r_w,z) = const_i$ in the 6 zones of the barrel's inner surface, i.e.: $\dot{q}_1 = 80\,\mathrm{MW/m^2}$, $\dot{q}_2 = 109\,\mathrm{MW/m^2}$, $\dot{q}_3 = 117\ \mathrm{MW/m^2}$, $\dot{q}_4 = 132\ \mathrm{MW/m^2}$, $\dot{q}_5 = 172\ \mathrm{MW/m^2}$, $\dot{q}_6 = 200\ \mathrm{MW/m^2}$ – see Fig. 2.

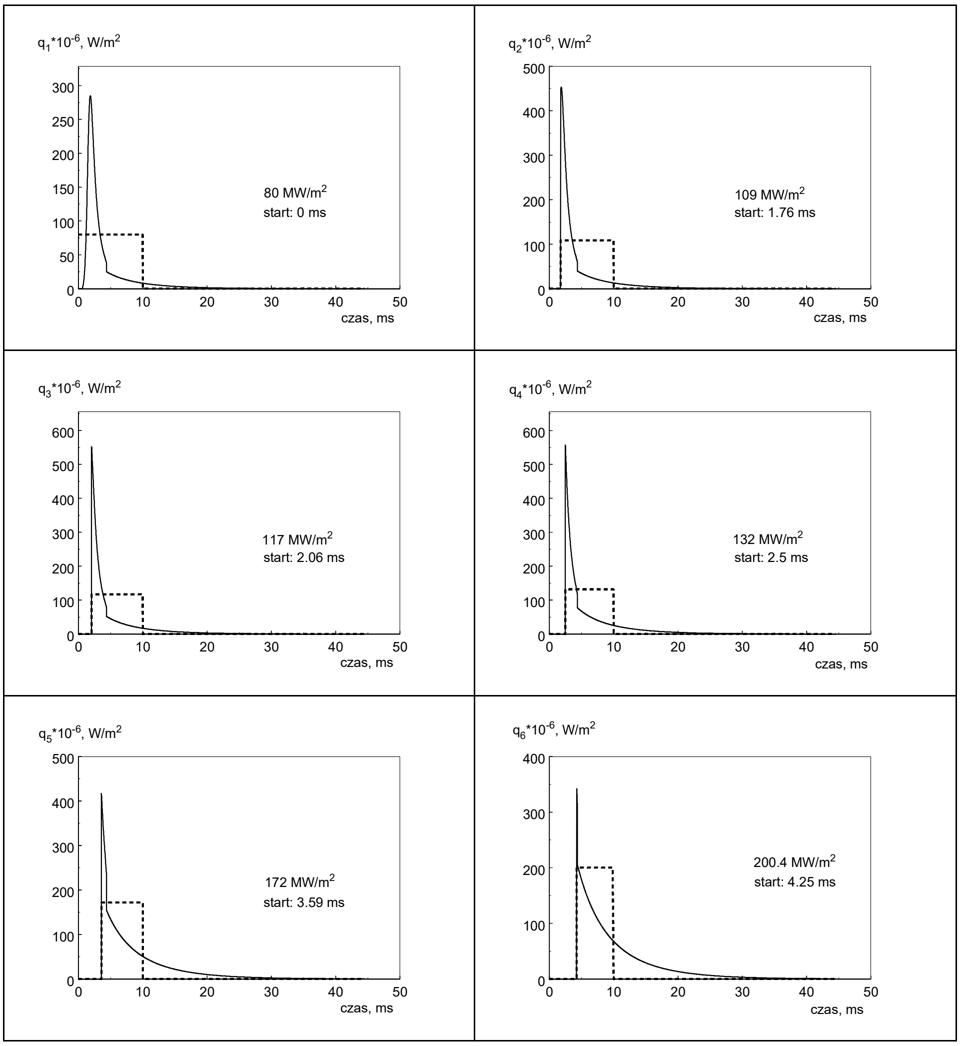

Fig. 2. Approximations of the relation $\dot{q}_i(t, r_w, z)$ as a function $\dot{q}_i(t, r_w, z) = const_i$ in the 6 zones S1 to S6 of the 35 mm anti-aircraft cannon barrel

The calculations were performed for two input data variants: (i) constant thermophysical parameter values of steel grade 32CrMoV12-28, with thermal conductivity λ = 30 W/(m·K), specific heat c_p = 550 J/(kg·K) and density ρ = 7850 kg/m^3; (ii) and with temperature-dependent specific heat c_p. The reference literature data of thermophysical properties for steel grade 32CrMoV12-28 cover a temperature range from ambient to 600ºC [3]. The thermal conductivity and density are virtually constant in this range, and the specific heat displays the most variation.

Because of this, the computer simulations included the relationship $c_p(T)$, resulting from a linear extrapolation of the values $c_p(T)$ at a temperature range above 600ºC: $c_p(T) = 460 + 0.1875*(T\text{-}293)$, temperature at [K] [3]. Note that the computer simulations of the heat transfer in the barrel wall during service life testing are largely within this temperature range.

2. THE INITIAL BOUNDARY VALUE PROBLEM

The paper presents the results of computer simulations of transient heat transfer in the wall of a 35 mm cannon barrel for a single shot and for a sequence of seven shots with a subsequent firing break. The initial temperature (WP) of the cannon was T_0 = 293 K. The heat transfer on the barrel's outer surface was assumed to be convection-based, i.e. $\dot{q} = -\alpha \cdot \left(T(t, r_z, z) - T_o\right)$.

A substitutive heat transfer coefficient value of α = 9.2 W/(m²·K) was assumed to be identical along the entire barrel's outer surface length. An initial boundary value problem was solved for the single shot, i.e. a non-stationary heat conduction equation with the boundary conditions of the third kind. The problem solved was two-dimensional and axially symmetrical [5]:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{c_p \cdot \rho}\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right] \tag{1}$$

with $r_w < r < r_z$, $0 < z < H$, $t > 0$ (2)

with the initial condition

$$T(0, r, z) = T_o \text{ with } r_w < r < r_z,\ 0 < z < H \text{, and } t = 0 \tag{3}$$

and the boundary conditions

$$\dot{q}_i(t, r = r_w, z) = const_i \text{ , } i = 1,..,6, \ (i - \text{a zone number from S1 to S6}) \tag{4}$$

$$\dot{q}(t, r = r_z, z) = \alpha\left(T(t, r = r_z, z) - T_o\right), \tag{5}$$

with: r_w = 35/2 mm, r_z dependent on the variable *z*.

The same initial boundary value problem was solved for the subsequent shots (1) to (5), where only the initial condition (WP) would change as resulting from the preceding shot calculations, $T(t_j, r, z) = T(0, r, z)$, with *j* being the shot sequential number. The boundary conditions (WB) remained unchanged. The calculations were performed with a finite element method in COSMOS/M software [6]. A grid of 14960 quadrilateral elements and 15983 nodes was used. A following division was assumed: into 110 sections along the radius and into 136 sections along the axis *z*. The barrel wall thickness changes along the axis (barrel length) *z*.

The grid was tapered along the radius r towards the barrel muzzle. Hence, in Section 6: Δr_1 = 0.12 mm = Δr_2 =…=Δr_i (i = 110), whereas in Section 4: Δr_1 = 0.38 mm = Δr_2 =…=Δr_i (i = 110). The calculation time for a single shot was assumed as equal to 100 ms. For burst firing, a sequence of 7 shots was used (0.1 s*7 shots = 0.7 s) with a firing break of 4.3 s (5 s-0.7 s = 4.3 s). The calculations were performed at 6 cross-sections of the barrel, i.e. from P1 to P6.

2.1. Calculation of heat transfer in the cannon barrel with a single shot

Prior analytic calculations [2] had demonstrated that the mean temperature increase of the barrel at Section 6 (with the highest thermal load) will be approx. 14 K after the first shot. Following subsequent shots in bursts, the temperatures would drop by ca. 0.1 K per round. To verify the analytical calculation results with computer simulations, the mean temperature rise of the barrel wall at specific sections (from P1 to P6) was calculated with the definition of the mean total temperature determined along the radius r at the cross-section (with equal spacing Δr_i (i = 110)):

$$\overline{T} = \frac{1}{r_z - r_w}\int_{r_w}^{r_z} T(r)dr = \frac{1}{\Delta r}\sum_{i=1}^{110}\left(T_i \cdot \Delta r_i\right) = \frac{\Delta r}{110 \cdot \Delta r}\sum_{i=1}^{110}\left(T_i\right) = \frac{1}{110}\sum_{i=1}^{110}\left(T_i\right) \tag{6}$$

and, ultimately: $\Delta T = \overline{T} - T_o$, with T_0 = 293 K.

The calculations of the mean temperature fields in the barrel wall for the first shot made with the consideration of the condition stating that a temperature-dependent specific heat output results in values not much higher than for the assumed constant values of thermophysical parameters. Hence the calculation results are illustrated only for the case with the relationship $c_p(T)$. Fig. 3 shows the computer simulation results for the relationships of temperature vs. time at the 6th cross-section (P6) of the barrel in the first 12 nodes between 0 and 100 ms. Fig. 4 shows the trends of the barrel's inner surface temperature changes in time at P1 to P6.

The mean barrel temperatures $\overline{T}_6$ at P6 in: 20 ms, 40 ms, 60 ms, 80 ms, and 100 ms in the case c_p = const. and $c_p(T)$ are listed in Table 1.

The mean barrel temperature $\overline{T}_6$ at P6 in 100 ms (up to the second shot) calculated from the expression (6) is 315.1 K; hence: $\Delta T = \overline{T}_6\left(t = 100\text{ ms}, r_{wew}, z_6\right) - 293\text{ K} = 315.1\text{ K} - 293\text{ K} = 22.1\text{ K}$.

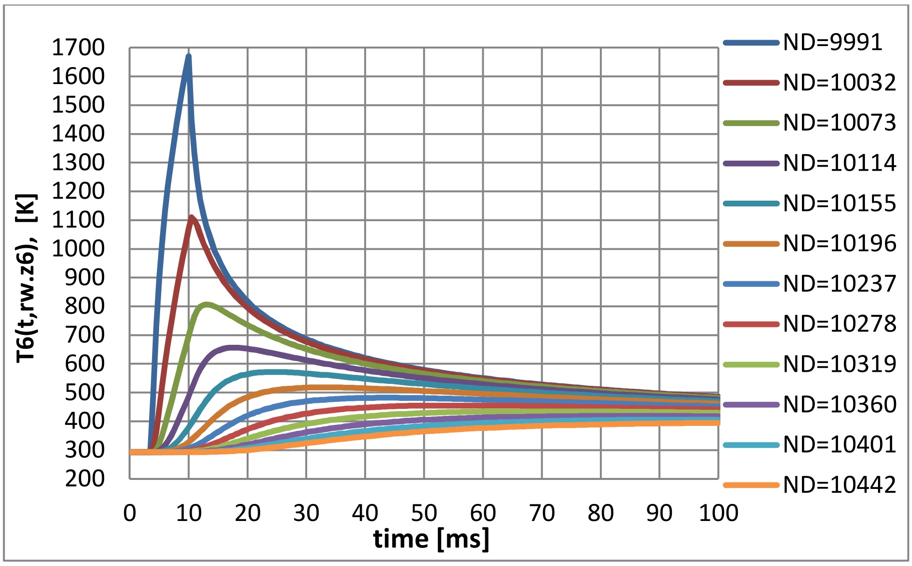

Fig. 3. Relationships of the temperature change vs. time trends at the barrel cross-section P6 in the first 12 nodes {node, radius r_w [mm]}: {9991, 17.50}, {10032, 17.62}, {10073, 17.75},…,{10442, 18.85}

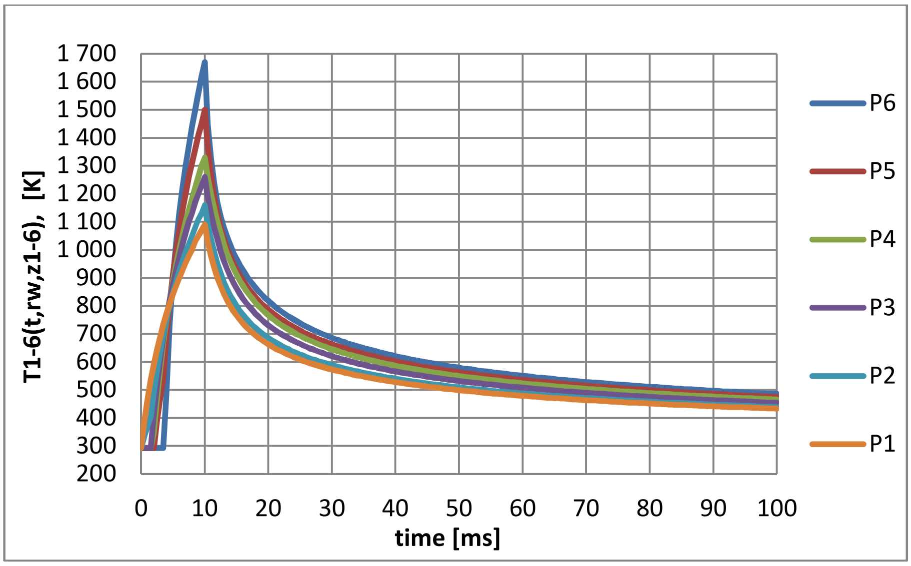

Fig. 4. Temperature distribution $T_{1\text{-}6}(t,r_w,z_{1\text{-}6})$ of the barrel's inner surface at the 6 cross-sections P1 to P6 for the single shot

The value ΔT of the mean temperature rise at the barrel cross-section P6 is therefore higher by ca. 8 K than the value from the analytical calculations [2]. Note that when the temperature trends are fast transient in the function of time, the calculations of the mean barrel temperature after the first shot with the thermal balance ($Q = mc_p\Delta T$) are rough approximations only. These rough approximations may be applied if the temperature is fast transient and yet similar across the entire volume. Here the situation is radically different. The heat pulse penetrates a small depth from the barrel's inner surface along the radius. The computer simulations show that following the first shot, the indicative heat penetration depth was ca. 4 mm (and 3.7 mm with c_p = const), see Fig. 5. Note that the data concerning temperature distribution and the heat penetration depth was determined for a model without a protective coating on the barrel's inner surface.

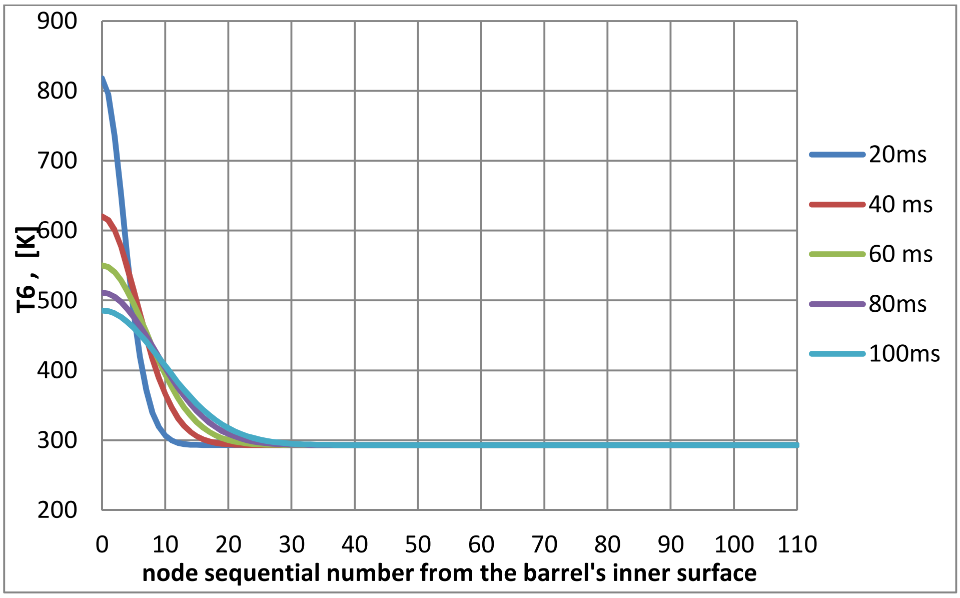

Fig. 5. Temperature distribution along the barrel radius at P6 between 20 ms to 100 ms at 20 ms intervals (node no. 33: 4.049 mm (0.1227 mm*33))

2.2. Calculation of the heat transfer in the cannon barrel for the 7th shot

The temperature of the inner surface after the 7th shot at the barrel cross-section 6 reaches its maximum values. At t = 610 ms, the temperature is 2190 K for c_p = const and 2310 K for $c_p(T)$.

Fig. 6 shows a comparison of the results of the computer-simulated temperature dependencies vs. time on the barrel's inner surface at P6 following the first shot and after the 7th shot, with the ranges of 0 to 100 ms (after the 1st shot) and 600 to 700 ms (after the 7th shot), respectively. As explained in Section 2.1, the impact of $c_p(T)$ on the temperature dependencies vs. time after the 1st shot is low. The differences are higher after the seventh shot, with $\Delta T_{max} = 2310 - 2190 = 120\,\mathrm{K}$. Fig. 7 shows the trends of the temperature changes along the barrel wall radius at P6 for the seven successive shots, i.e. times 100 ms, 200 ms, 300 ms, 400 ms, 500 ms, 600 ms, and 700 ms in the case $c_p(T)$. After the 7th shot, the heat penetration depth reached node 75, i.e. 9 mm into the barrel wall (8 mm with c_p = const), see Fig. 7. The mean barrel temperatures at P6 in: 620 ms, 640 ms, 660 ms, 680 ms and 700 ms are shown in Table 1. Following a burst of 7 shots, the mean temperature at P6 rose by 127.7 K (420.7 – 293 = 127.7 K), see Table 1.

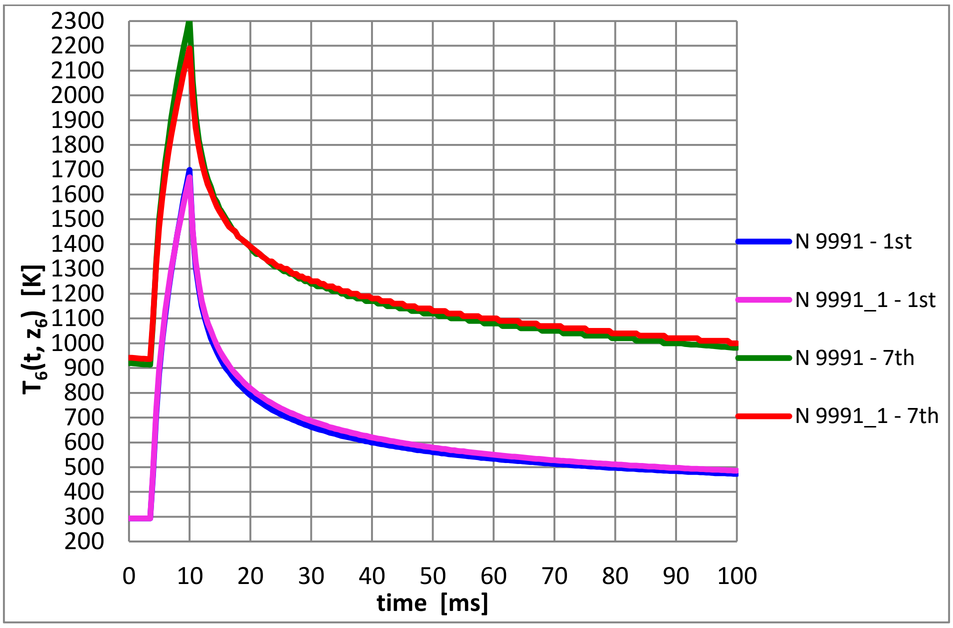

Fig. 6. Temperature change dependencies vs. time on the barrel surface P6 for shot 1st and shot 7th: 1st, 7th – c_p = const, 1_1st, 1_7th – $c_p(T)$

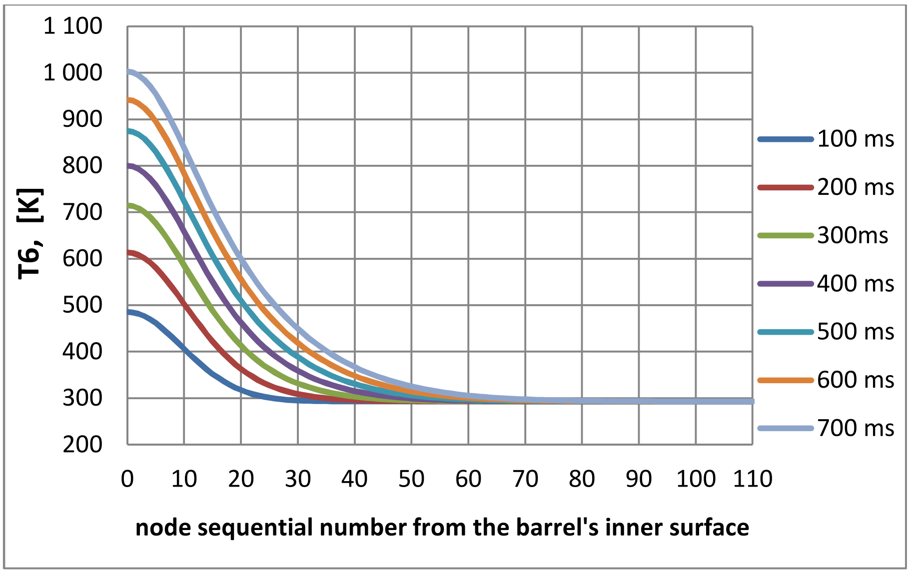

Fig. 7. Temperature distribution along the barrel radius *r* at P6 in 100 ms, 200 ms, 300 ms, 400 ms, 500 ms, 600 ms, and 700 ms, respectively

2.3. Calculations of the heat transfer in the cannon barrel in 4.3 s after the 7th shot

The mean barrel temperatures $\overline{T}_6$ at P6 from 700 ms to 5 s with c_p = const and $c_p(T)$ are listed in Table 1. In 4.3 s after the seventh shot, the temperature at P6 dropped to 412.2 K, down to ca. 139ºC. The temperature change trends along the barrel radius at P6 in 700 ms, 800 ms, and from 1 to 5 s are shown in Fig. 8. The temperature change trends for the barrel's inner surface (at cross-sections P1 to P6) from 0 to 5 s are shown in Fig. 9. The calculations of the barrel outer surface temperatures at P6 vs. time revealed that from $t = 1$ s, the temperature was T_o and subsequently displayed a linear growth to 360 K (ca. 87ºC) at $t = 5$ s. Moreover, Table 2 shows a comparison of the computer-simulated maximum temperature values T_m at P6 of the barrel's inner surface during the 7-shot burst $c_p(T)$ to the results produced with c_p = const.

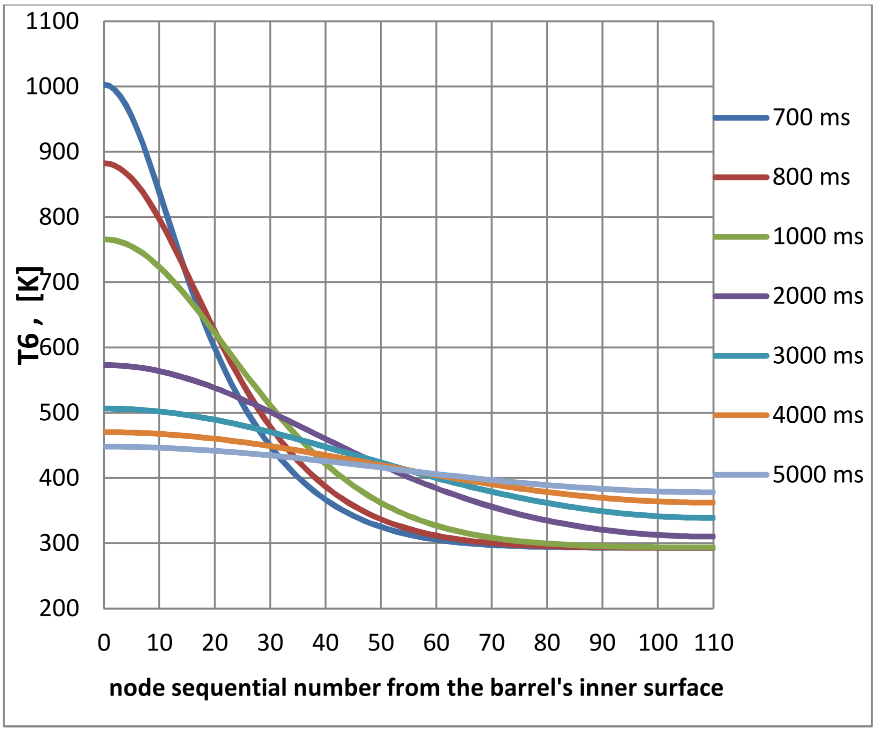

Fig. 8. Temperature distribution along the barrel wall radius *r* at P6 in: 700 ms, 800 ms and from 1 s to 5 s at 1 s intervals

Considering the relationship $c_p(T)$, the maximum temperature on the barrel's inner surface T_m at P6 during the 7th shot is lower by $\Delta T = 120$ K , than with c_p = const.

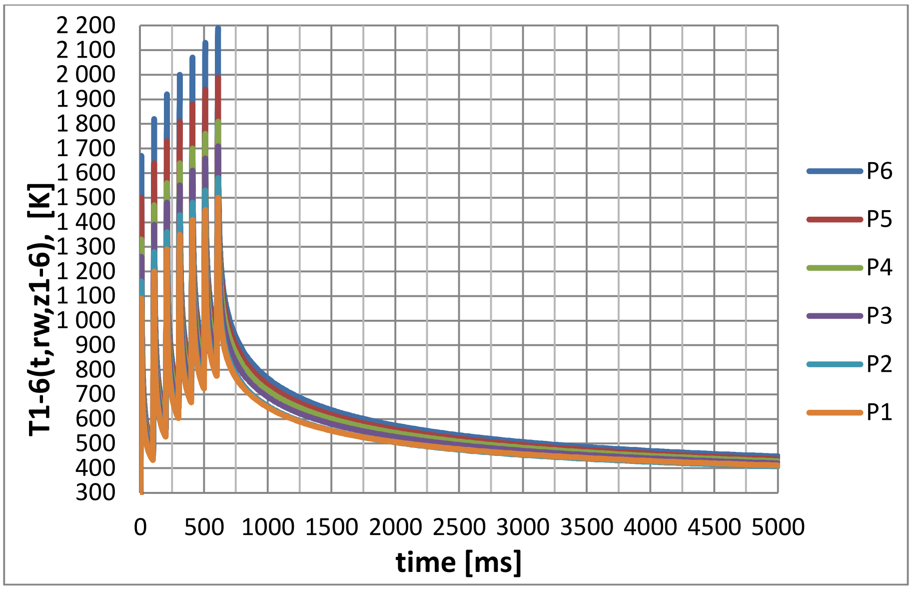

Fig. 9. Temperature distribution $T_{1\text{-}6}(t,r_w,z_{1\text{-}6})$ on the barrel's inner surface at P1 to P6 for the burst of seven shots and the subsequent firing break of 4.3 s

Table 1. Mean barrel temperatures $\overline{T}_6$ at P6 following the first shot and after a burst of 7 shots with the firing break

1st shot			7th shot			4.3 s after the 7th shot		
t, ms	$\overline{T}_6$, K; c_p=const	$\overline{T}_6$, K; $c_p(T)$	t, ms	$\overline{T}_6$, K; c_p=const	$\overline{T}_6$, K; $c_p(T)$	t, ms	$\overline{T}_6$, K; c_p=const	$\overline{T}_6$, K; $c_p(T)$
20	314.4	316.4	620	424.2	431.6	800	410.6	429.6
40	313.4	315.8	640	422.7	431.0	1000	409.7	428.0
60	312.9	315.5	660	421.8	430.7	2000	404.6	421.5
80	312.6	315.3	680	421.2	430.5	3000	401.0	417.2
100	312.4	315.1	700	420.7	430.3	4000	398.5	414.2
						5000	396.8	412.2

Table 2. Maximum barrel temperatures T_m on the barrel's inner surface at P6 with the 7-shot burst and inclusive of the relationship $c_p(T)$ to the results produced with c_p = const

1st shot			**2nd shot**		
t, ms	T_m, K; c_p=const	T_m, K; $c_p(T)$	t, ms	T_m, K; c_p=const	T_m, K; $c_p(T)$
10	1700	1670	110	1870	1820
3rd shot			**4th shot**		
210	1990	1920	310	2090	2000
5th shot			**6th shot**		
410	2170	2130	510	2240	2130
7th shot					
610	2310	2190			

3. CONCLUSIONS

The model of heat transfer in the anti-aircraft cannon barrel presented herein, which considers no protective coating on the barrel's inner surface, is relatively simple. Hence the obtained computer analysis results should be deemed only as indicative and approximate and requiring experimental verification. The experimental verification will be the subject of further investigations the more so because the number of barrel zone divisions and the initial boundary value conditions can be easily coupled with experimental data.

Although simple, the model presented herein can be very useful already at the discussed stage of research. The thermal analysis results obtained for a solid barrel wall can be indicative for a proper design of the protective coating for the barrel bore surface.

Moreover, all calculations presented herein assumed that the heat flux density vs. time on the barrel's inner surface was identical for the first and subsequent shots. In reality, the heat flux density on the barrel's inner surface will be slightly lower in subsequent shots (as compared to the first shot) and will drop with each successive shot due to the increasing temperature of the barrel's internal surface. The higher the barrel's inner surface temperature is, the better is the shielding performance of this temperature relative to the heat emission from the combustion of the propellant in successive shots.

It is then expected that the mean barrel temperature rise values following each successive shot will be slightly lower than the ones presented herein. The analysis of the computer simulation results provides important information about the maximum temperature of the uncoated barrel's inner surface T_m at cross-section P6; the value exceeds the manufacturer's maximum permissible limit of 1074 K (800ºC) already after the first shot.

Note that what is of the essence is the total residence time of the barrel surface material at temperatures of 1074 K during the burst of 7 shots. The time values are shown for cross-sections P1 to P6 with $c_p(T)$ in Table 3.

Table 3. Total residence time of the barrel material at above 800ºC in the 7-shot burst

Cross-section	P1	P2	P3	P4	P5	P6
Total time for 7 shots, ms	69	81	114	143	164	203

The results of temperature records for the 35 mm anti-aircraft cannon barrel during the scheduled live-fire tests and complementing the existing model with material properties of the protective coating on the barrel's inner surface will facilitate a more comprehensive computer model of barrel heat exchange in firearm and artillery weapons of various calibres.

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Analiza wymiany ciepła w 35 mm lufie armaty przeciwlotniczej

Andrzej DĘBSKI, Piotr KONIORCZYK, Zbigniew LECIEJEWSKI, Marek PREISKORN, Zbigniew SURMA, Janusz ZMYWACZYK

Wydział Mechatroniki i Lotnictwa, Wojskowa Akademia Techniczna, ul. gen. Sylwestra Kaliskiego 2, 00-908 Warszawa

Streszczenie. W pracy przedstawiono wyniki symulacji numerycznych nieustalonego przewodzenia ciepła w ściance lufy armaty kalibru 35 mm dla pojedynczego strzału oraz dla sekwencji serii siedmiu strzałów i następującej po niej przerwy. Lufa armaty została wykonana ze stali 32CrMoV12-28. Modelując zjawisko, przyjęto założenie, że materiał ścianki lufy jest jednolity, a wewnętrzna powierzchnia lufy nie zawiera powłoki ochronnej w postaci warstwy chromu galwanicznego lub warstwy azotowanej. Obliczenia wykonano w dwóch wariantach danych wejściowych, tzn. przy stałych wartościach parametrów termofizycznych oraz gdy ciepło właściwe zależy od temperatury. Lufę o długości całkowitej 3150 mm podzielono na 6 stref. W każdej strefie, na powierzchni wewnętrznej lufy zadano inne wartości gęstości strumienia ciepła w postaci funkcji prostokątnych $\dot{q}_i(t, r_w, z) = const_i$ w zakresie od 0 do 10 ms (z przesunięciem startu t_i funkcji $\dot{q}_i$ w kolejnych strefach). Czas obliczeń dla pojedynczego strzału założono równy 100 ms. Obliczenia wykonano metodą elementów skończonych za pomocą programu COSMOS/M.

Słowa kluczowe: wymiana ciepła, lufa armaty przeciwlotniczej