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Selected Aspects of Heat Transfer Study in a Gun Barrel of an Anti-Aircraft Cannon

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Abstract. The paper presents the results of computer simulations of the transient heat flow in the barrel wall of a 35 mm caliber cannon for a single shot and a sequence of seven shots for a selected 30HN2MFA barrel steel. It was assumed that the inner surface of the barrel does not have a protective layer of chromium or nitride. When calculating heat transfer in a barrel, constant and temperature variable values of thermal conductivity, specific heat and density (in the range from RT (Room Temperature) up to 1000°C) in the 30HN2MFA steel were assumed. The test results were compared for both cases. A barrel with a total length of 3150 mm was divided into 6 zones (i = 1,…, 6) and in each of them, the heat flux density was calculated as a function of the time $\dot{q}_i(t)$ on the inner surface of the barrel. In each zone, the heat transfer coefficient, as a function of the time $h_i(t)$ and bore gas temperature as a function of the time $T_g(t)$ to the cannon barrel for given ammunition parameters, was developed. A calculating time equaling 100 ms per single shot was assumed. The results of the calculations were obtained using FEM implemented in COMSOL Multiphysics ver. 5.6 software.
Keywords: mechanical engineering, anti-aircraft cannon barrel, heat transfer, numerical simulation, temperature field

1. INTRODUCTION

Since 2012, works for the Polish Navy related to the construction of a new Polish autonomous maritime reconnaissance system have been underway in the scientific and industrial consortium (Polish Naval Academy in Gdynia, Military University of Technology in Warsaw, PIT-RADWAR S.A. in Warsaw and ZM "Tarnów" S.A. in Tarnów). The above mentioned system has been tested on the ORP Kaszub corvette since 2016. It is a modular system, the main element of which is a 35 mm automatic naval cannon, an integrated tracking head and a fire control station. The process of creating this system is an inspiration to solve many scientific problems for example in the field of testing the effectiveness of fire control algorithms or ballistics when firing a 35 mm caliber barrel [1-5].

In this study, an initial boundary value problem (IBVP) of heat transfer in the barrel wall of a 35 mm caliber cannon made of 30HN2MFA steel was solved for a single shot and the sequence of seven shots for constant and temperature-dependent thermophysical properties of this steel. The calculations were made using FEM introduced in COMSOL Multiphysics in the same way as in [2]. The barrel with a total length of 3150 mm was divided into 6 zones S1 to S6 – Fig. 1. The heat transfer coefficient as a function of the time $h_i(t)$ in 6 sections P1 to P6: P1: z = 216 mm, P2: z = 385 mm, P3: z = 535 mm, P4: z = 880 mm, P5: z = 2081 mm, P6: z = 2980 mm (z in the range from 0 to 3150 mm) and gas temperature as a function of the time $T_g(t)$ was adopted from [2] – Fig. 2. The functions $h_i(t)$ in sections P1 to P6 are valid in the zones S1 to S6. The S0 zone of the cannon breech was distinguished in the range from 0 to 216 mm, which – at the present stage of research – was assigned to the same function $h_i(t)$ as the S1 zone. Additionally, in the discussion chapter, the authors compared the heat transfer analysis results in this cannon with the results presented in [1, 4].

Thus, on the inner surface of the barrel in each zone, the authors adopted different values of heat flux density expressed by: 1) rectangular functions $\dot{q}_i(t, r_{in}, z) = const$ in the range from 0 to 10 ms (with the shift of the beginning of t_i of the function $\dot{q}_i$ shifted in subsequent zones), 2) in the form $\dot{q}_i(t, r = r_{in}, z) = h_i(t) \cdot \left(T_0 - T_g(t, r_{in}, z)\right)$ and 3) in the form $\dot{q}_i(t, r = r_{in}, z) = h_i(t) \cdot \left(T(t, r_{in}, z) - T_g(t, r_{in}, z)\right)$.

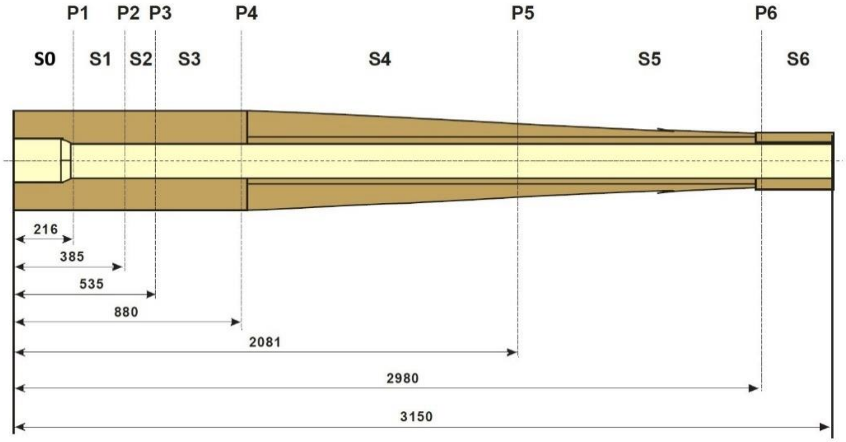


Fig. 1. Heat transfer zones S1 to S6 of the 35 mm cannon barrel input to the calculations: S1: 0÷385 mm, r_{out} = 55.0-55.0 mm; S2: 385÷535 mm, r_{out} =55.0-57.0 mm; S3: 535÷880 mm, r_{out} =57.0-59,5 mm; S4: 880÷2081 mm, r_{out} = 59.5-44.07 mm; S5: 2081÷2980 mm, r_{out} = 44.07-31.0 mm; S6: 2980÷3150 mm, r_{out} = 31.0 mm. The zone S1 includes the zone S0 of the cannon breech [1-2, 4].

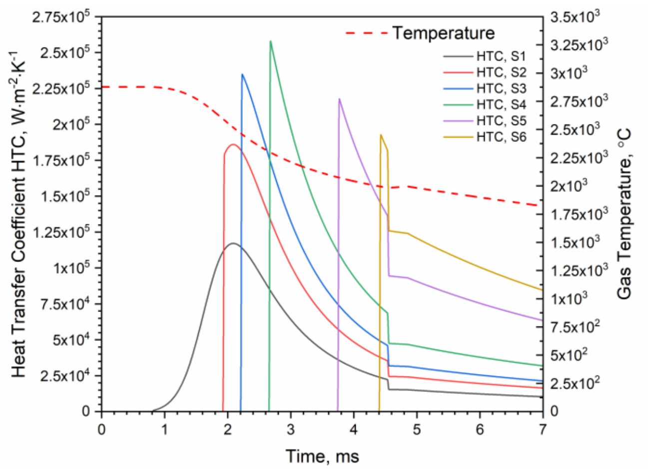


Fig. 2. Heat transfer coefficient (HTC) as a function of the time $h_i(t)$ in the 6 cross-sections P1 to P6 and the gas temperature as a function of the time $T_g(t)$ for the 35 mm anti-aircraft cannon barrel [**2**].

2. THERMOPHYSICAL PROPERTIES OF THE 30HN2MFA BARREL STEEL

Thermophysical properties, i.e., thermal conductivity, specific heat, and density as a function of temperature in the RT range up to 1000°C, were taken as input data for the IBVP in the barrel wall of a 35 mm caliber cannon, as shown in Tables 1 and 2. The data between measurement points were approximated in COMSOL software using cubic splines [2, 6-8].

Table 1. Data on thermal conductivity, specific heat, and density of the 30HN2MFA barrel steel [2, 6-7].

30HN2MFA					
T[°C]	k_s $[W \cdot m^{-1} \cdot K^{-1}]$	T[°C]	$c_s[J \cdot g^{-1} \cdot K^{-1}]$	T[°C]	$\rho_s[g \cdot cm^{-3}]$
54.2	35.9	38	0.440	50	7.77
149.1	37.3	70	0.462	100	7.75
250.0	36.0	100	0.475	200	7.72
352.0	33.8	150	0.492	400	7.65
453.3	30.9	200	0.505	600	7.59
553.6	27.2	250	0.517	700	7.55
651.1	19.7	300	0.528	720	7.55
704.4	17.1	350	0.539	725	7.55
723.0	16.0	400	0.550	730	7.55
743.3	15.8	450	0.560	735	7.55
763.0	17.1	500	0.569	740	7.55
783.1	18.7	550	0.579	750	7.57
802.8	19.3	600	0.589	765	7.58
822.9	19.5	650	0.598	770	7.59
842.8	19.7	700	0.607	775	7.59
904.9	20.3	750	0.616	785	7.59
1004.3	20.6	800	0.625	800	7.58
		850	0.634	900	7.53
		900	0.642	1060	7.46
		991	0.658		

The constant values of the thermophysical properties of the 30HN2MFA barrel steel are presented in Table 2. The thermophysical properties of 30HN2MFA steel were taken from own research as the average in the range from RT (room temperature) to 400°C [6].

Table 2. Data on thermal conductivity, specific heat, and density of the 30HN2MFA barrel steel as a constant values [6]

T[°C]	k_s $[W \cdot m^{-1} \cdot K^{-1}]$	$c_s[J \cdot g^{-1} \cdot K^{-1}]$	$\rho_s[g \cdot cm^{-3}]$
average from range RT-400°C	34	0.550	7.77

3. INITIAL BOUNDARY VALUE PROBLEM

The initial temperature of the cannon was T_0 = 20°C. The heat transfer on the barrel's outer surface was modelled as a boundary condition of the 3rd kind in a form $\dot{q} = h_{out} \cdot (T(t, r_z, z) - T_0)$. An equivalent heat transfer coefficient value of h_{out} = 9.2 W/(m²K) was assumed to be the same on the entire surface of the barrel. The governing equation for nonlinear and axially symmetrical 2D IBVP is as follows [2, 9-11]:

$$\rho_s(T) c_s(T) \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(k_s(T) r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_s(T) \frac{\partial T}{\partial z}\right) \tag{1}$$

with $\quad r_{in} < r < r_{out}, \quad 0 < z < l_m, \quad t > 0,$ (2)

where:

T is the temperature of a gun barrel,
t is the time,
r is the distance between node and the barrel axis line,
ρ is the density of barrel material,
c is the specific heat of barrel material, with the initial condition:

$$T(0, r, z) = T_0 \text{ with } r_{in} < r < r_{out} \qquad 0 < z < l_m \text{ and t = 0} \tag{3}$$

and the boundary conditions:

$$\dot{q}_i(t, r = r_{in}, z) = h_i(t) \cdot \left(T(t, r_{in}, z) - T_g(t, r_{in}, z)\right),\ i=1,\ldots,6, \tag{4}$$

(i – a zone number from S1 to S6)

$$\dot{q} = h_{out} \cdot (T(t, r_{out}, z) - T_0), \tag{5}$$

where T_g is the gas temperature calculated by solving the internal ballistic model, r_{in} = 35/2 mm, r_{out}, dependent on the variable z – Fig. 1.

The same IBVP was solved for the subsequent shots, Eq. (2) to (5), where only the initial condition 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 remained unchanged during calculations.

4. TEMPERATURE DISTRIBUTION IN THE CANNON BARREL FOR A SINGLE SHOT

For the 30HN2MFA barrel steel, the temperature distributions $T_i(t, r_{in}, z)$ of the barrel's inner surface at the 6 zones S1 to S6 (z in the middle of each zone) for the single shot are shown in Fig. 3. In each zone, the heat transfer coefficient as a function of the time $h_i(t)$ is different – Fig. 2. The dashed line in each figure shows the time the bullet left the barrel (t = 4.54 ms).

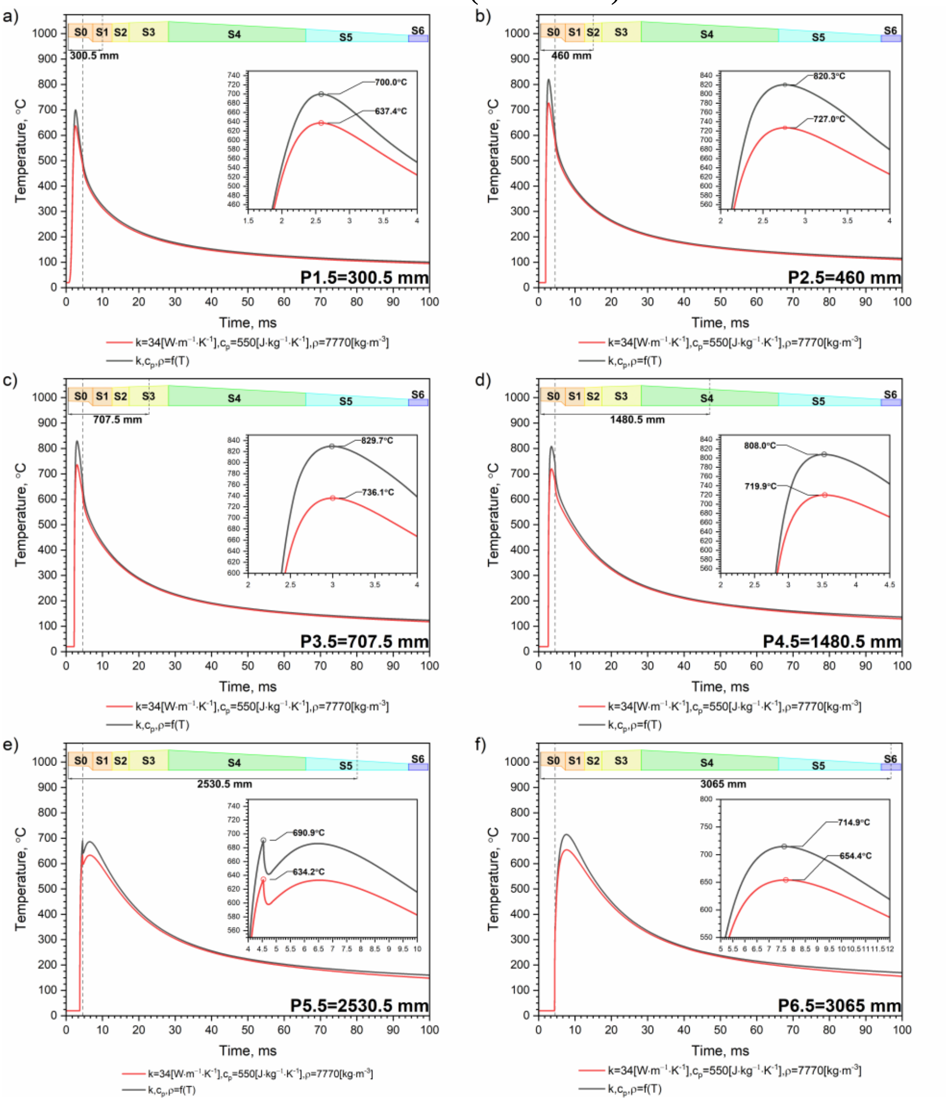


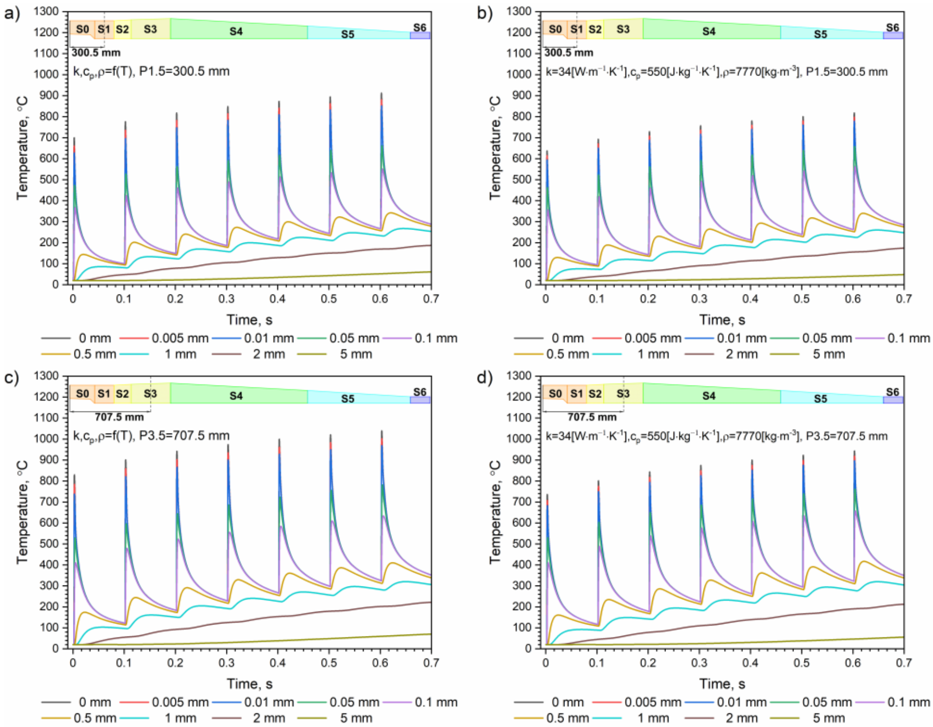
Fig. 3. The temperature distribution $T_i(t, r_{in}, z)$ of the barrel's inner surface at the 6 zones S1 to S6 for a single shot for the thermophysical properties of constant and variable as a function of temperature

The maximum of the highest temperature, i.e., the so-called highest peak temperature occurs for the temperature-dependent thermophysical properties of the 30HN2MFA barrel steel. In this case, the highest temperature is about 100°C higher than with constant thermophysical properties, most in the zones S2 and S3.

5. TEMPERATURE DISTRIBUTION IN THE CANNON BARREL FOR A SERIES OF SEVEN SHOTS

For the 30HN2MFA barrel steel, the temperature distributions $T_i(t, r, z)$ along the barrel thickness for constant and temperature-dependent thermophysical properties, in three sections S1, S3, and S6 (z in the middle of each zone) for a series of seven shots are shown in Fig. 4.

The lowest peak base temperatures, i.e., so-called the lowest temperatures are read after each shot, i.e., for t=100 ms for the first shot, 200 ms for the second shot, etc. It can be assumed that the temperature of the inner surface of the barrel during a series of shots is equal to the lowest peak base temperatures and to the barrel temperature at a depth of 0.5 mm below its surface, i.e., $T_i(t, r = r_{in}\text{-}0.5\text{ mm}, z)$ – Fig. 4.



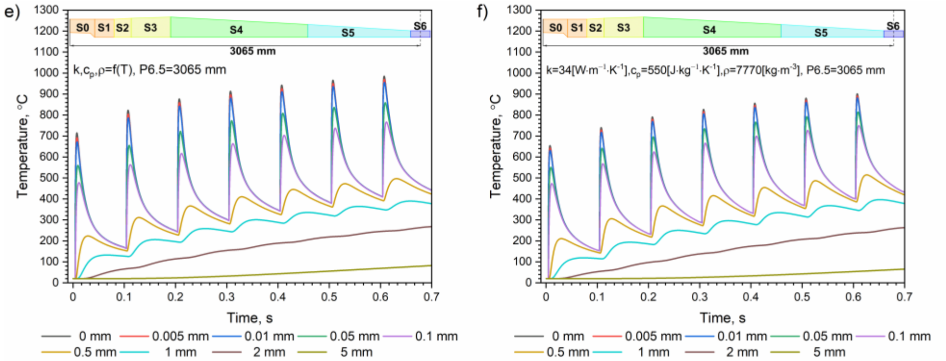
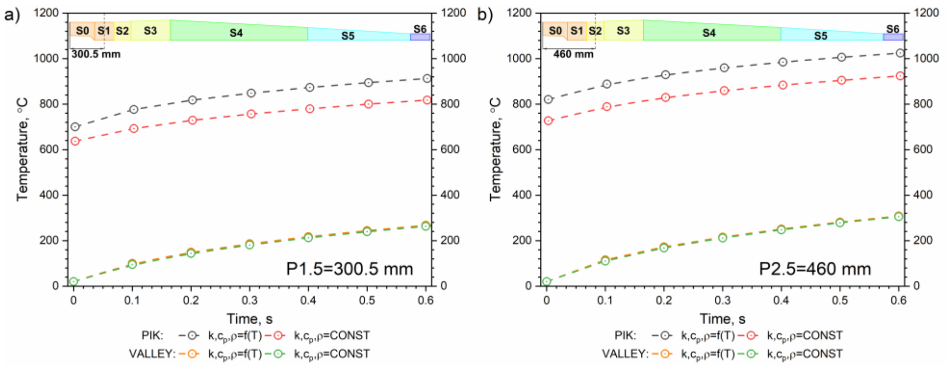


Fig. 4. The temperature distribution $T_i(t, r, z)$ along the barrel thickness at the 3 zones S1, S3, and S6, for the sequence of seven shots: left side – for the thermophysical properties of variable as a function of temperature, i.e., $k, c_p, \rho = f(T)$ [2]; right side - for the thermophysical properties of constant, i.e., $k, c_p, \rho = const.$: black line – on the inner surface of the barrel, red line – 0.005 mm below the inside surface, blue line – 0.01 mm below the inside surface, and so on.

6. ENVELOPE OF THE LOWEST AND THE HIGHEST TEMPERATURES IN THE BARREL

Figure 5 shows the envelopes of the highest peak temperatures and the lowest peak temperatures for the case of constant and temperature-dependent thermophysical properties for 7 shots.

For the temperature-dependent thermophysical properties, in the six sections S1 to S6, for each of seven shots, the highest temperature is approximately 100°C higher than for the constant thermophysical properties – Fig. 5. For each of the seven shots, the lowest temperatures, i.e., the lowest peak temperatures are similar in the both cases.



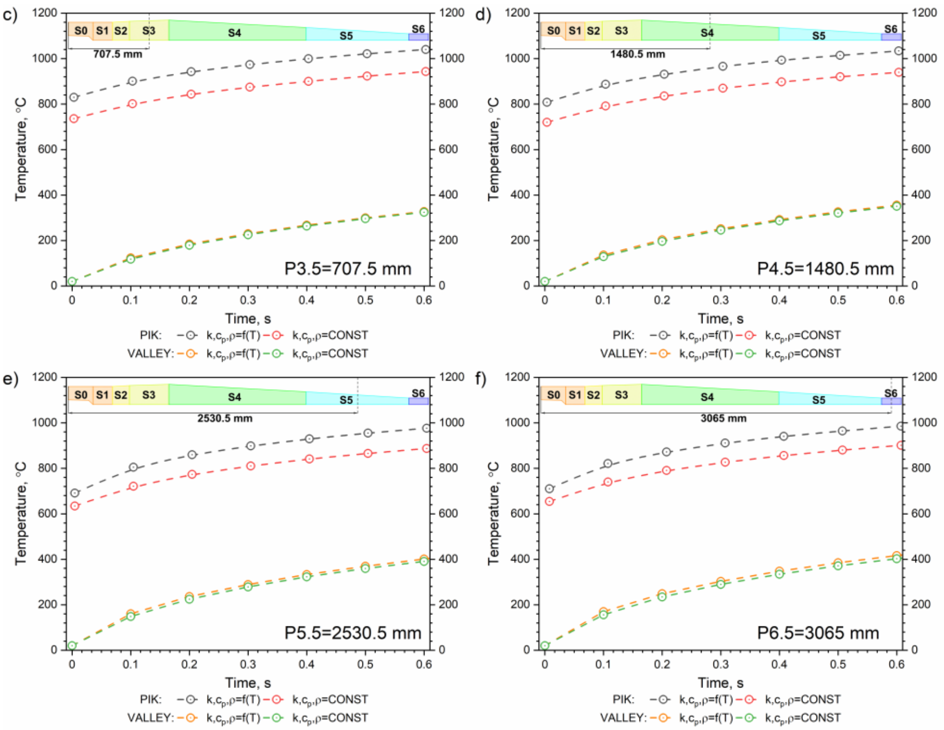


Fig. 5. Envelope of the lowest and the highest temperatures of the inner surface at the 6 zones S1 to S6 for the sequence of seven shots, for the thermophysical properties of variable as a function of temperature, i.e., $k,c_p,\rho = f(T)$ [2] and for the thermophysical properties of constant, i.e., k,c_p,ρ = const.

7. DISCUSSION

In 2016, the authors of this paper presented the results of computer simulations of the transient heat flow in the barrel wall of a 35 mm gun for a single shot and a sequence of seven shots, assuming that on the inner surface of the barrel in each of the 6 zones, different values of heat flux density were expressed as the rectangular functions $\dot{q}_i = const_i$ 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) [1]. The calculation time for a single shot was assumed as equal to 100 ms [1].

The calculations were performed with a finite element method in COSMOS/M software. The heat flux density was taken as rectangular functions because it was not known if the problem would be solved with such high heat flux density values.

In this paper, the results of computer simulations of the transient heat flow in the same wall of the 35 mm gun barrel were repeated for a single shot, assuming that the heat flux densities are expressed as: 1) rectangular functions $\dot{q}_i = const_i$; 2) in the form $\dot{q}_i(t, r = r_{in}, z) = h_i(t) \cdot \left(T_0 - T_g(t, r_{in}, z)\right)$; 3) in the form $\dot{q}_i(t, r = r_{in}, z) = h_i(t) \cdot \left(T(t, r_{in}, z) - T_g(t, r_{in}, z)\right)$ – Fig. 6.

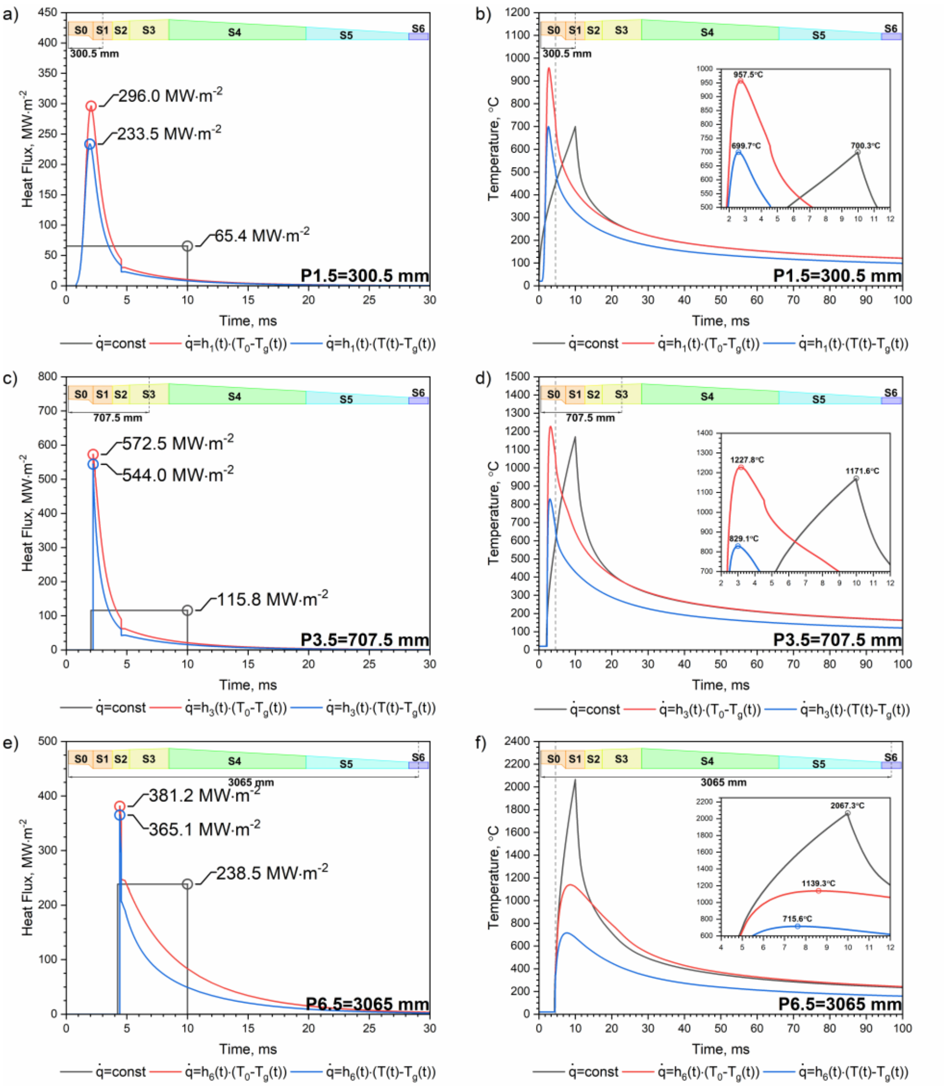


Fig. 6. Different approximations of the relation $\dot{q}_i(t, r_{in}, z)$ in the 3 zones S1, S3, and S6 – left side of the figure. The temperature distribution $T_i(t, r_{in}, z)$ of the barrel's inner surface at the same zones – right side of the figure.

The calculations were made for constant thermophysical properties of the 30HN2MFA barrel steel using FEM implemented in COMSOL Multiphysics ver. Software 5.6 - Table 2

The assumption of the heat flux density as a rectangular function shifts the maximum of the highest temperature towards a longer time and changes the shape of the $T(t, r_{in}, z)$ function.

8. CONCLUSIONS

In this paper, the simulations of heat transfer in the barrel of the 35 mm anti-aircraft gun were carried out for constant and temperature-dependent thermophysical properties of the 30HN2MFA barrel steel. The results of the numerical calculations are summarized as follows:

1. in each zone, i.e., S1 to S6, the highest temperature, i.e., the highest peak temperature for the first and seven shots, is approximately 100°C higher for the temperature-dependent thermophysical properties of the 30HN2MFA barrel steel than for the assumed constant values of the thermophysical properties of this steel – Figs. 3÷5;
2. it can be assumed that the lowest peak base temperatures and the temperature of the barrel at a depth of 0.5 mm below its surface are equal to each other, and it can be assumed that these are the temperatures of the inner surface of the barrel – Fig. 4;
3. the lowest peak base temperatures are similar for the temperature-dependent thermophysical properties of the barrel steel and assuming that the thermophysical properties are constant – Fig. 5;
4. taking the heat flux density as a rectangular function delays the appearance of the highest maximum temperature and changes the shape of the function $T(t, r_{in}, z)$ - Fig. 6.

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Wybrane aspekty badania wymiany ciepła w lufie działa przeciwlotniczego

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Streszczenie. W pracy przedstawiono wyniki symulacji komputerowych nieustalonego przepływu ciepła w ścianie lufy armaty kalibru 35 mm dla pojedynczego strzału i sekwencji siedmiu strzałów dla wybranej stali lufowej 30HN2MFA. Założono, że wewnętrzna powierzchnia lufy nie posiada ochronnej warstwy chromu lub azotku. Przy obliczaniu wymiany ciepła w lufie przyjęto stałe oraz temperaturowo zmienne wartości przewodności cieplnej, ciepła właściwego i gęstości (w zakresie od temperatury pokojowej (Room Temperature) do 1000°C) dla stali 30HN2MFA. Wyniki badań porównano dla obu przypadków. Lufa o łącznej długości 3150 mm została podzielona na 6 stref (i=1,…,6) i w każdej z nich obliczono gęstość strumienia ciepła w funkcji czasu $\dot{q}_i(t)$ na wewnętrznej powierzchni lufy. W każdej strefie obliczono współczynnik przejmowania ciepła w funkcji czasu $h_i(t)$ oraz temperatury gazów prochowych w funkcji czasu $T_g(t)$ w lufie armaty dla zadanych parametrów amunicji. Dla pojedynczego strzału do obliczeń przyjęto czas równy 100 ms. Wyniki obliczeń uzyskano za pomocą MES zaimplementowanego w oprogramowaniu COMSOL Multiphysics ver. 5.6.

Słowa kluczowe: inżynieria mechaniczna, lufa działa przeciwlotniczego, wymiana ciepła, symulacje numeryczne, pole temperatury