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THEORETICAL AND EXPERIMENTAL STUDY OF THE UNSTEADY HEAT TRANSFER IN THE BARREL WALL OF THE ARMAMENT SYSTEM

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Abstract: *In this paper it is presented a study of the unsteady heat transfer in the barrel wall of the armament system during the firing. The connection with the processes which take places inside the barrel is realized by using as input data the bore temperature and the convective heat transfer coefficient, obtained with the aid of the interior ballistics codes. The differential equation of heat conduction for a stationary, homogeneous and isotropic solid with no internal heat source was employed for the theoretical study of transient diffusion in the wall of barrel. The numerical solution of the differential equation was obtained by explicit finite difference method. The theoretical results and the experimental data are also compared.*

Keywords: *heat transfer in barrel wall of armament system, transient diffusion, mathematical model, numerical solution, explicit difference method, interior ballistic codes, specific simplifying assumptions*

1. INTRODUCTION

During the firing with armament system the temperature of barrel increases, producing several adverse effects on the overall system. The accuracy is diminished with repeated firings due to thermal distortion of the barrel. The barrel wears increases with temperature. Also, the heating of the barrel due to firing rate and the number of rounds fired can influence the thermal characteristics of the subsequent round. Knowing that the temperature is increasing during the firing with armament system, it is possible to establish a suitable firing rate, in the case of small caliber armament or the using of barrel cooling devices, in the case of large caliber armament.

Due to the complexity of heat transfer in the barrel of armament system the following assumptions are accepted:

- The armament system is supposed to have smooth barrel;
- The heat conduction in the axial direction may be neglected relative to that in the radial direction;
- The flow in direction of the inside barrel may be neglected;
- The thermal expansion of the metal barrel may be omitted;
- The metal of the barrel is stationary, homogeneous and isotropic medium;
- The density, specific heat at constant pressure and the thermal conductivity coefficient of metal are taken to be constant;
- The internal heat source does not exist.

The differential equation of heat conduction for a stationary, homogeneous and isotropic solid with no internal heat source was employed for the theoretical study of transient diffusion in the wall of the barrel. The numerical solution of the differential equation with initial and boundary conditions was obtained by explicit finite difference method.

The connection with the processes which take places inside the barrel is realized by using as input data the bore temperature and the convective heat transfer coefficient, obtained with the aid of interior ballistics codes.

The theoretical results were compared with experimental data in the case of the 76, 2-mm caliber armament system.

2. THE MATHEMATICAL MODEL

The mathematical modeling of heat conduction is realized with the aid of fundamental equation of thermal conductivity

$$\rho c_p \frac{\partial T}{\partial t} = k\Delta T + f(x,y,z,t) \quad (1)$$

where:

ρ - The density of metal [kg/m^3];

c_p - The specific heat at constant pressure of metal [J/(kgK)];

k - The thermal conductivity coefficient of metal [J/(msK)];

Δ - The Laplace operator;

$f(x,y,z,t)$ - The heat source density in every point of metal, at a certain moment;

T - The temperature of metal [K];

t - The time [s];

x, y, z - The Cartesian coordinates.

Taking into account the previous assumptions, the differential equation (1) becomes

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \quad (2)$$

where $a = k/(\rho c_p)$ is the thermal diffusivity.

In cylindrical coordinates r, φ, z, the differential equation (2) is written

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right), \quad (3)$$

where r is radial coordinate.

For the numerical integration of equation (3) the following limit conditions (initial and boundary conditions) are used:

- The initial condition at a z given:

$$T(r,0) = T_a,\ t = 0,\ r_i \le r \le r_e; \quad (4)$$

- The boundary conditions:

a. At the inner wall of the barrel:

$$-k\frac{\partial T}{\partial r} = h_g\left(T_g - T\right);\ t > 0;\ r = r_i; \quad (5)$$

b. At the outer wall of the barrel:

$$k\frac{\partial T}{\partial r} = 0;\ t > 0;\ r = r_e, \quad (6)$$

where:

T_a - The ambient temperature of the atmosphere;

r_i - The radial coordinate at inner wall of the barrel;

r_e - The radial coordinate at outer wall of the barrel;

T_g and h_g - The cross-sectional average temperature of the powder gases inside the barrel at time t and displacement z, irrespective, the coefficient of heat transfer.

The values of T_g and h_g are obtained with the aid of interior ballistics codes which are elaborated on the basis of mathematical models of the core flow and the flow in boundary layer inside the barrel during the ballistic cycle.

3. INTEGRATION OF THE MATHEMATICAL MODEL

Taking into account the differential equation (3), the initial condition (4) and the boundary conditions (5) and (6), the variation of temperature in the barrel wall during the ballistic cycle can be determined by solving the equations system:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right); \quad (7a)$$

$$T(r,0) = T_a; \quad (7b)$$

$$k\frac{\partial T}{\partial r} - h_g\left(T_g - T\right) = 0; \quad (7c)$$

$$\frac{\partial T}{\partial r} = 0. \quad (7d)$$

It is difficult to have the exact solving of this equations system because the coefficient of the heat transfer h_g and the cross-sectional average temperature of the powder gases inside barrel T_g are magnitudes which vary during the ballistic cycle.

The numerical solving of the system (7) can be realized by approximation of partial differential equations with finite difference formulas.

With the following notations:

δt - The time increment for calculation of temperature profile;

δr - The radial distance between two adjacent nodal points,

and $A = \dfrac{a\delta t}{(\delta r)^2}$,

the equation (7a) in finite difference is written

$$\frac{T_{m,n+1} - T_{m,n}}{\delta t} = a\left(\frac{T_{m+1,n} - 2T_{m,n} + T_{m-1,n}}{(\delta r)^2} + \frac{1}{r}\frac{T_{m+1,n} - T_{m-1,n}}{2\delta r}\right) \quad (8)$$

or

$$T_{m,n+1} = A\left(1 - \frac{\delta r}{2r}\right)T_{m-1,n} + (1-2A)T_{m,n} + A\left(1 + \frac{\delta r}{2r}\right)T_{m+1,n}, \quad (8')$$

It is observed that it is necessary to impose a positive condition for the second term from the right part of the equation (8'), so

$$1 - 2A = 1 - \frac{a\delta t}{(\delta r)^2} > 0. \quad (9)$$

From relation (9) it is obtained the condition for the time increment δt, namely

$$\delta t < \frac{(\delta r)^2}{a}. \quad (10)$$

The equations (7c) and (7d) in finite difference become:

$$k\frac{T_{m+1,n} - T_{m-1,n}}{2\delta r} - h_g\left(T_g - T\right) = 0; \quad (11)$$

$$\frac{T_{m+1,n} - T_{m-1,n}}{2\delta r} = 0. \quad (12)$$

At the inner wall the of barrel ($r = r_i$), the relation (8') becomes

$$T_{0,n+1} = A\left(1 - \frac{\delta r}{2r}\right)T_{-1,n} + (1-2A)T_{0,n} + A\left(1 + \frac{\delta r}{2r}\right)T_{1,n}. \quad (13)$$

From relation (11), written at the inner wall of the barrel, it is obtained

$$T_{-1,n} = \frac{2\delta r h_g}{k}\left(T_g - T_{0,n}\right) + T_{1,n}. \quad (14)$$

If it is taken into account the relation (14), then relation (13) becomes

$$T_{0,n+1} = A\left(1 - \frac{\delta r}{2r}\right)\left[T_{1,n} + \frac{2\delta r h_g}{k}\left(T_g - T_{0,n}\right)\right] + $$
$$+ (1-2A)T_{0,n} + A\left(1 + \frac{\delta r}{2r}\right)T_{1,n} \quad (15)$$

or

$$T_{0,n+1} = \left[1 - 2A - \frac{2A\delta r h_g}{k}\left(1 - \frac{\delta r}{2r}\right)\right]T_{0,n} + $$
$$+ 2AT_{1,n} + \frac{2A\delta r h_g}{k}\left(1 - \frac{\delta r}{2r}\right)T_g. \quad (15')$$

At the outer wall of the barrel ($r = r_e$), the relation (8') becomes

$$T_{NN,n+1} = A\left(1 - \frac{\delta r}{2r}\right)T_{NN-1,n} + $$
$$+ (1-2A)T_{NN,n} + A\left(1 + \frac{\delta r}{2r}\right)T_{NN+1,n}. \quad (16)$$

From relation (12), written at the outer wall of barrel, it is obtained

$$T_{NN+1} = T_{NN-1}, \quad (17)$$

where NN is number of nodal points.

If it is taken into account the relation (17), than the relation (16) becomes

$$T_{NN,n+1} = 2AT_{NN-1,n} + (1-2A)T_{NN,n}. \quad (18)$$

With the aid of relations (8'), (15') and (18) it is possible to calculate the temperature in wall of the barrel for a time increment δt.

4. RESULTS

On the basis of relations (8'), (15') and (18) it was elaborated a computer code which provides the temperature profile in the wall of the barrel.

In Fig. 1 there are presented the curves of temperature variation for different moments of time (t_1=0.0024s; t_2=0.0048s; t_3=0.0072s; t_4=0.0096s; t_5=0.012s, t_6=0.0144s; t_7=0.1681s; t_8=0.0168; t_9=0.0192; t_{10}=0.0216s) in the wall of the barrel at the first firing.

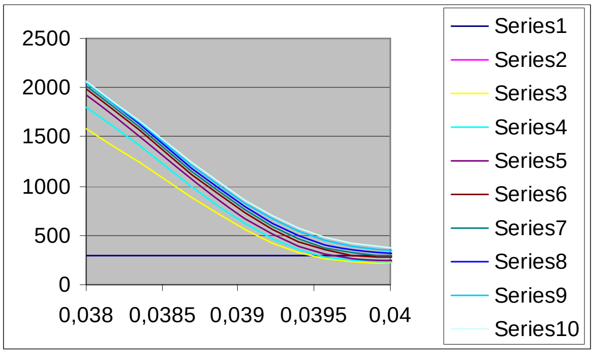

Figure 1 Repartition of temperature in wall of the barrel

In Fig. 2 there are shown the variation of temperature at inner and outer wall of barrel in function of time.

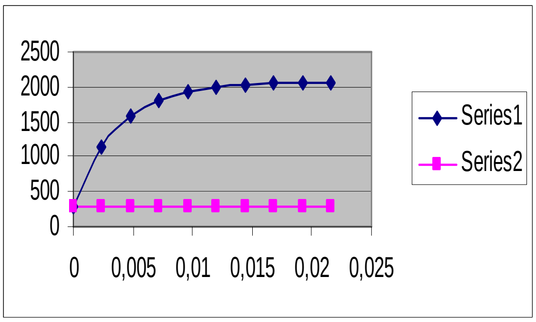

Figure 2 Variation of temperature at inner and outer wall of the barrel versus time

From Fig. 2 it is observed that the temperature at inner wall of the barrel increases rapidly at beginning of ballistic cycle, reaching approximately 90% from its maximum value. After this moment, the temperatures at inner wall of the barrel increase slowly although the temperature of the outer layers of barrel wall continues to increase. In the case of a single round, i. e. for very short time, the outer surface of the barrel wall does not succeed to increase too much the temperature.

If more rounds are fired, the temperature of inner surface of the barrel wall will increase. The history of temperature increasing in this case in the inner surface of the barrel wall, accepting the assumption that next round is fired immediately, is presented in Fig. 3.

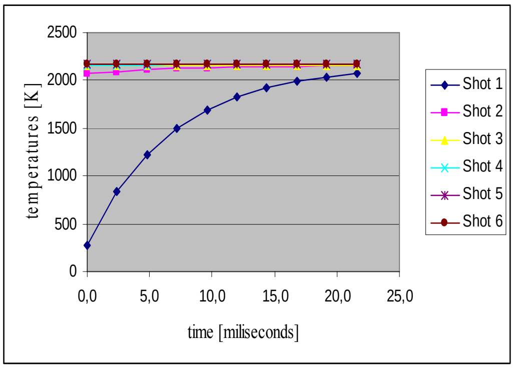

Figure3 The history of temperature increasing in the inner surface of the barrel wall

5. CONCLUSIONS & ACKNOLEWLEDGMENT

5.1 The theoretical results. The validation of the mathematical model of the unsteady heat transfer in the barrel wall of the armament system is made by the comparison of the theoretical results for the temperatures of the outer surfaces of the barrel of an existent gun with the experimental data measured in the case of the same gun.

The theoretical results are those provided by the computer code elaborated on the basis of the relations and equations included in this paper. The experimental data have been collected by measurements at the firing place.

5.2 The experimental data. The experimental data are the temperatures of the outer surfaces of the 76, 2 mm caliber barrel, information gathered during the firing of the 6 rounds in the firing place. The pyrometers Micronics OS 524 E type was used for measuring the outer surface barrel gun (Fig. 4).

Figure 4 The pyrometers Micronics OS 524 E type

This no contact thermometer measures the surface temperature without touching it and it determines the value of temperature on the basis of the infrared radiation (IR) of an object. The captured radiation intensity depends on the temperatures of the surface and the emissivity of the material (barrel steel).

The basic procedure for temperature measuring consists of aiming the thermometer at the target and touching the trigger. On the basis of all carried out settings the display shows the current temperature value.

Due to the safety measures taken in the firing place, the temperatures of the outer surface barrel were measured before gun loading and after firing each shot.

Simultaneously, the main internal ballistic data such as firing such as: maximum pressure values and the projectile velocity values were measured for each round.

In Table 1, the experimental data are presented.

No. of round	Velocity at the muzzle of barrel [m/s]	Maximum pressure Kgf/cm^2]	Temperatures [K] **before** firing	Temperatures [K] **after** firing	Time between firings [sec.]
1	662,8	2315	278	289	-
2	672,4	2344	288	298	140
3	671,7	2349	296	306	141
4	657,9	2307	305	314	125
5	667,5	2319	313	321	139
6	673,7	2297	320	328	123

Table 1. The experimental data

On the basis of the experimental data presented in Table 1, Figure 5 was drawn.

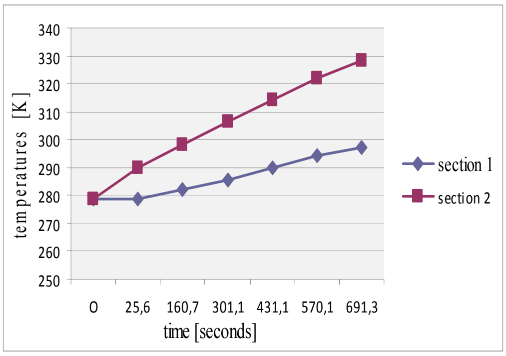

Figure 5 The history of temperatures on the outer surfaces barrel on the two sections

5.3 The comparison between the theoretical results and the experimental data. In order to validate the mathematical model for unsteady heat conduction in the barrel wall of the artillery system, the theoretical results and the experimental data are compared.

In Table 2 are presented the theoretical results and experimental data referring to the temperatures of the outer surface on the section 2 of the barrel, after firing.

No of round / details	Temperatures [K]					
	1	2	3	4	5	6
Section 2						
Experi-mental data	289	298	306	314	321	328
Theore-tical results	278	278	278	278	278	278,1
Diffe-rences [%]	3,9	7,1	9,1	11,4	13,6	15,2

Table 2. The experimental results and theoretical data

5.4 Conclusions. According to Table 2, the differences between the theoretical results and the experimental data and presented are small, this allowing the validation of the mathematical model of the unsteady heat conduction in the barrel wall of the armament system.

Those differences are generated both by the external conditions of the firing place and by the assumptions taken on the beginning of the mathematical modeling. Thereby:

- The procedure used for temperatures measurement is different from the calculation process of the barrel wall temperatures. In the calculation process, the input data for the current firing are the same with the exit data for the previous firing. That fact reduces very much the time for the heat transfer in the barrel;

- The simplifying assumptions at the beginning of the mathematical model contribute to removing from the real phenomenon of the heat transfer in the barrel wall of the armament system. According to one of these assumptions, there is not heat transfer from the outer surface of the barrel to the surrounding medium. Actually, at the level of the outer surface, the free convection and the external radiation of heat are the same order.

REFERENCES

1. **CORNER, J.** *Theory of Interior Ballistics of Guns*. New York-London (1950).
2. **DĂNĂILĂ, S., BERBENTE, C.** *The numerical methods in fluid dynamics.* Bucureşti: The Romanian Academy Publishing House (2003).
3. **FISHER, M.** *A Contribution to the Heat Transfer and Prediction of Wear in Small Caliber Barrels*. Proceedings of the 2nd Conference on Barrel Weapon System. Brno (1997).
4. **FRANCO, P., PETER, H.,** *Gun Barrel Erosion: Study of Thermally Insulating Layers.* Proceedings of the 19th International Symposium of Ballistics. Interlaken (2001).
5. **GERBER, N., BUNDY, M. L.** *Heating of a Tank Gun Barrel: Numerical Study.* Memorandum Report BRL-MR-3962. Maryland (1991).
6. **MORARU, F.** *Numerical analysis chapters. Applications in External Ballistics and Flight Dynamics.* Bucharest: Military Technical Academy Publishing House (1995).
7. **SABAC, I. G.** *Special Maths (vol. I and II).* Bucharest: Didactical and Pedagogical Publishing House (1965).