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# Differences in Barrel Chamber and Muzzle Deformation during Shot

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**Abstract:**

*The paper deals with mechanical parameters calculations of the barrel muzzle and barrel chamber. These calculations have been carried out for 30mm ballistic barrel. We aimed at elastic bore displacement, elastic tangential surface strain and powder gas pressure. Analytic and finite elements calculations were employed. The propellant gases and thermal load were considered together. There is temperature distribution at barrel muzzle which has been computed for experimental barrel.*

**Keywords:**

*Barrel, chamber, muzzle, barrel bore, strain, stress, field of temperature.*

## 1. Introduction

This paper deals with the calculation of selected mechanical parameters of gun barrel. It is mainly about the calculation of elastic radial deformation of the bore and relative elastic tangential deformation of the external surface of the barrel. Elastic radial deformation of the bore causes the release of propellant gases from the barrel and affects the quality of guidance of projectile in the bore. Relative elastic tangential deformation of the external surface of the barrel can be used mainly to assess the nature of the load in a given location. Both these deformations arise as a result of the load of the bore by gas pressure generated by burning the powder charge.

These calculations have been carried out for a 30mm ballistic barrel (Fig. 1). ANSYS Workbench 13 and autoCAD 2008 have been used for calculations.

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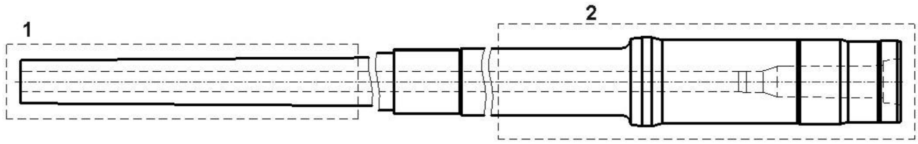


*Fig. 1 Experimental ballistic barrel, cal. 30 mm . 1 – muzzle part, 2 – chamber part*

## 2. FEM Calculation of Elastic Deformation of Barrel Chamber Part under Load by Gas Pressure

FEM (finite element method) model of the chamber for loading the bore by propellant gas pressure is solved as an axially symmetric task in the overall axial length model 595 mm. Slotting guide section is not considered and the bore radius of the grooved bore is taken 15.45 mm, lands lies on the safe side of calculation. Rifling is not possible to enter when solving an axial symmetric task. When modelled by FEM, the model had to be solved as the volume task. Although the groove depth (height field) compared with cross of barrel wall is small, it will need a large network density at the groove. When used, the length of the model would be exceeding the allowable number of elements of the academic license program ANSYS.

Shooting pressure impacts simultaneously on the borehole wall, base of projectile and bottom chamber [1]

$$p_d > p > p_s \tag{1}$$

where $p_d$ is the breech pressure (Pa),
$p$ is the space-mean pressure of propellant gases (Pa),
$p_s$ is the pressure on the base of projectile (Pa), see Fig.2.

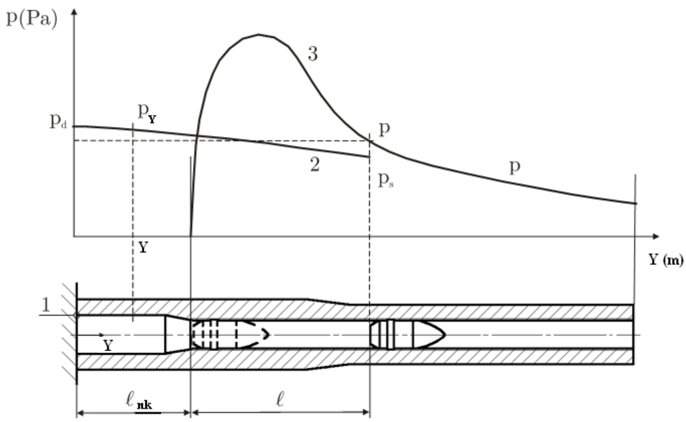


*Fig. 2 Distribution of pressure in the space behind projectile: 1 – start of the loading of the barrel from propellant gas pressure in the radial direction, 2- pressure distribution in the space behind the projectile, 3 – mean ballistic pressure*

Measurement has found the maximum pressure acting on the bottom of the cartridge in the experimental barrel: $p_d$ = 309.87 MPa. In this case, the projectile was located at a position shown in Fig. 3:

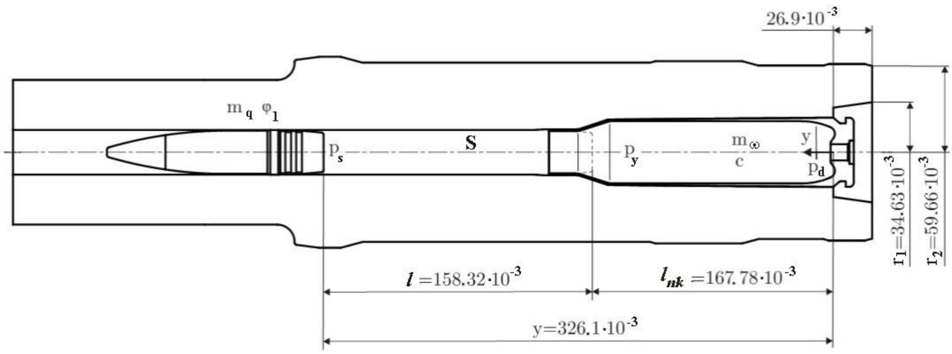


*Fig. 3 Chamber – the situation of the projectile when $p_d$ is maximum*

Data of projectile travel, pressure of propellant gases, main geometric parameters and mass characteristics of ammunition:

length of initial combustion volume: $l_{nk}$ = 167.78 mm,
travel of projectile: $l$ = 158.32 mm,
initial combustion volume: $c_0 = 227 \times 10^{-6}$ m$^3$,
calibre of projectile: $d$ = 0.03 m,
coefficient of fictivity [5]: $\varphi_1$ = 1.03,
mass of propellant: $m_\omega = 202.5 \times 10^{-3}$ kg,
mass of projectile: $m_q = 370 \times 10^{-3}$ kg,
maximum breech pressure $p_d$ = 309.9 MPa.

Pressure $p_s$ is given by relation

$$p_s = \frac{p_d}{1 + \frac{1}{2}\lambda_\chi \frac{m_\omega}{\varphi_1 m_q}} \tag{2}$$

where $\lambda_\chi = \frac{l_{nk} + l}{l_0 + l}$; the reduced length of initial combustion volume: $l_0 = \frac{c_0}{0.82 d^2}$.

$$p_y = p_s \left\{ 1 + \frac{1}{2}\lambda_\chi \frac{m_\omega}{\varphi_1 m_q} \left[ 1 - \frac{y^2}{(l_{nk} + l)^2} \right] \right\} \tag{3}$$

where $p_y$ is the function of pressure between breech and the base of projectile,
$y$ is the axial distance measured from the bottom of the cartridge – the beginning of the coordinate system.

During the projectile motion inertia force $F_z$ (N) operates in the chamber

$$F_z = 0.7954 \frac{m_B}{m_R} p_m d^2 , \tag{4}$$

where $m_B$ is the weight of own barrel, $m_R$ is the weight of all recoil parts, $p_m$ is the maximum pressure.

Input data for calculation of the inertia force at the maximum gas pressure are: $m_B$ = 125 kg, $m_R$ = 278.03 kg, $p_m = p_d$ = 309.9 MPa and $F_z$ = 99730 N.

The inertia force $F_z$ (N) is calculated as the maximum axial force from the inertial force for annulus of back face of barrel, see Fig. 3: $r_1$ = 34.63 mm, $r_2$ = 59.66 mm. Calculation of pressure in the annulus:

$$-p_{r_1 r_2} = \frac{F_z}{\pi(r_2^2 - r_1^2)}, \tag{5}$$

$$-p_{r_1 r_2} = 13457664 \text{ Pa}.$$

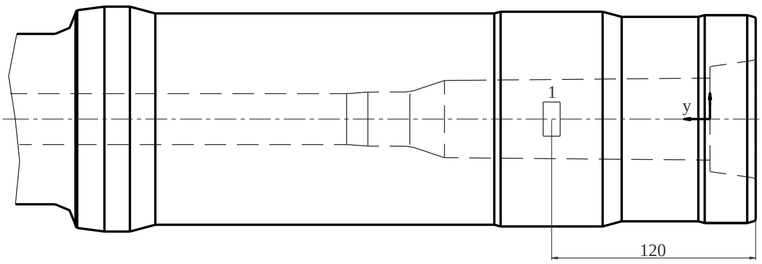


*Fig. 4 Calculation point of elastic relative tangential deformation on external surface of the chamber part. 1 – calculation point*

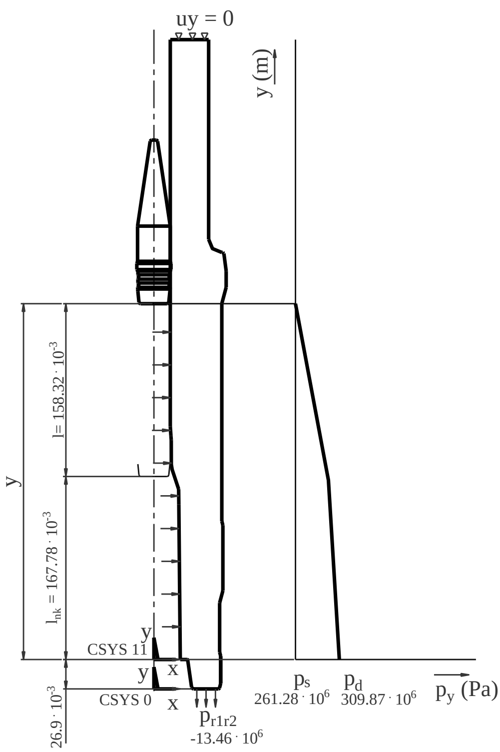


*Fig. 5 Geometry of axially symmetric FEM model of chamber and pressure load CSYS 0- global Cartesian coordinate system, CSYS 11- local Cartesian coordinate system, indicated by the fictitious location of shot*

FEM model contains two Cartesian coordinate systems: the global system CSYS 0, which is located in the centre of the back face of the barrel, and the local one CSYS 11, which is located in the centre of the bottom of the fictitious cartridge.

The pressure function $p_y$ (Pa) is the force condition entered into the model. The local coordinate system CSYS 11 is applicable (see Fig. 5). The processor of ANSYS was entered in the detail section of the load as (in original notation):

function = 261.3e6 · (1 + 0.186 · (1 – ({*Y*}^2/0.106))) (Pa; m),

where *Y* is the *y* coordinate (m) in the local coordinate system CSYS 11.

One of the advantages of FEM software applications lies in the comfort of mechanical calculation of the required parameters. The following figure (Fig. 6) shows the calculated relative elastic deformation of the chamber.

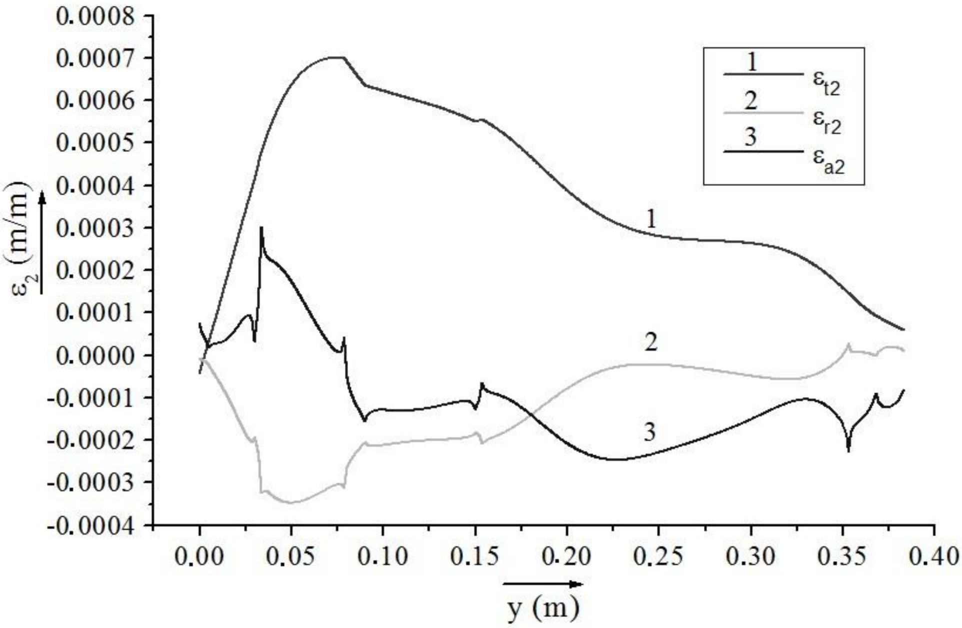


*Fig. 6 Elastic relative deformation in the chamber part*

FEM calculated elastic relative tangential deformation of the external surface (Fig. 3): For place (1), axial distance $y$ = 0.12 m CSYS 0: $\varepsilon_{t2}$ = 611.67 μm/m.

## 3. FEM Calculation of Elastic Deformation of Barrel Muzzle Part

### *3.1. FEM Calculation of Elastic Deformation of Barrel Muzzle Part under Load by the Gas Pressure*

FEM model of the muzzle for loading the bore by propellant gas pressure is solved as an axially symmetric task in the overall axial length model 500 mm. Slotting guide section is also neglected (at the bore radius of the grooved bore is taken 15.45 mm). The beginning of global Cartesian coordinate system CSYS0 $y$ = 0 m is identified with the centre of barrel muzzle.

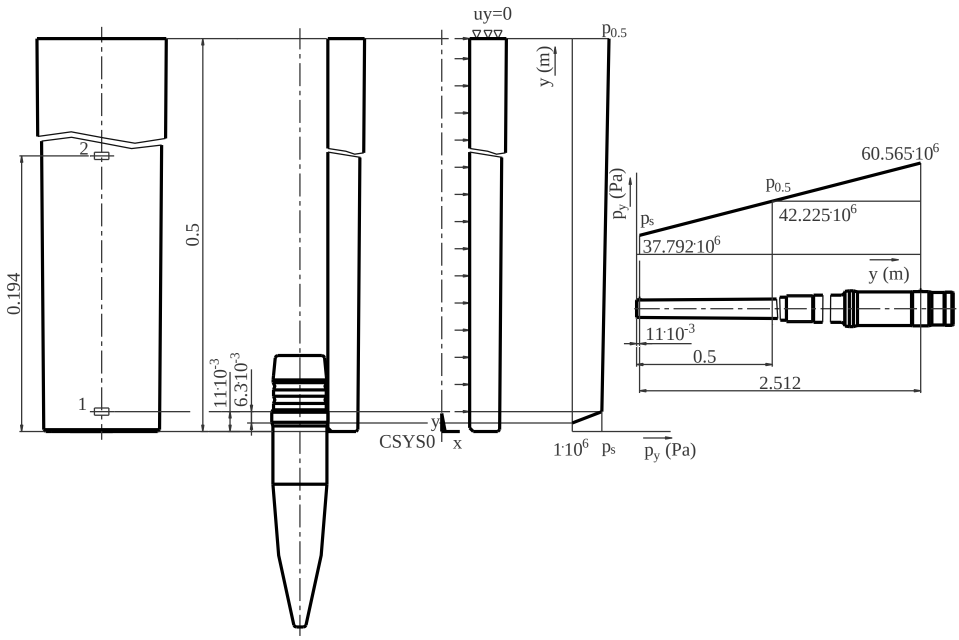


*Fig. 7 Geometry model of muzzle part and load of gas pressure:*
*1, 2 – calculation points, CSYS0 – global Cartesian coordinate system*

By measuring at the distance $y = 11$ mm from the muzzle, the pressure was found: $p_s = 37.792$ MPa. This value was measured when the base of projectile underneath the pressure sensor. Axial length from the end of the guide ring to the base of projectile is small, so we have chosen $p_s = 37.792$ MPa when the guide ring runs underneath the pressure sensor.

The pressure 37.792 MPa near the muzzle and the pressure 60.565 MPa in the chamber were measured at the same time. Radial pressure drop between these points is taken to vary linearly, because the parabolic course of pressure in the space behind projectile (Fig. 2) is the following long distance. Using a simple linear relation function we can calculate for the pressure when $y = 0.5$ m ($p_{0.5}$), $p_{0.5} = 42.225$ MPa.

In the developing of the model [6, p. 59], the value of 1 MPa (Fig. 7) was in accordance with taking into account propellant gas leakage along a contacted position of the guide ring on the space between 6.3 mm and from value $p_s = 37.792$ MPa.

Two points of FEM calculation of the relative elastic tangential deformation $\varepsilon_{t2}$ (m/m) of the external surface of the barrel are shown in Fig. 7. The first place is far from the muzzle of the axial distance $y = 11$ mm, the second one is at a distance $y = 194$ mm

$$\varepsilon_t = \frac{1}{E}[\sigma_t - \mu(\sigma_r + \sigma_a)];\ \varepsilon_r = \frac{1}{E}[\sigma_r - \mu(\sigma_t + \sigma_a)];\ \varepsilon_a = \frac{1}{E}[\sigma_a - \mu(\sigma_r + \sigma_t)] \quad (6)$$

where: $E$ is the modulus of elasticity (Pa), $\mu$ is Poisson's ratio (-), $\sigma_t$ is the tangential stress (Pa), $\sigma_r$ is the radial stress (Pa) and $\sigma_a$ is the axial stress (Pa).

Relations for radial and tangential stresses (for the case of plane stress, $\sigma_a = 0$ (Pa)) are also known from the literature, but they are used in mathematically modified form [1]:

$$\sigma_t = p_y \frac{r_1^2}{r^2} \frac{r^2 + r_2^2}{r_2^2 - r_1^2} ; \sigma_r = -p_y \frac{r_1^2}{r^2} \frac{r_2^2 - r^2}{r_2^2 - r_1^2} \tag{7}$$

where: $p_y$ is the internal pressure in solved place of barrel (Pa), $r_1$ is the internal radius of barrel in solved place (m), $r_2$ is the outer radius of barrel in solved place (m), and $r$ is the instantaneous radius of the investigated point in the wall of barrel (m).
When $r = r_2$, then the relative elastic tangential deformation $\varepsilon_{t2}$ is calculated as follows

$$\varepsilon_{t2} = p_y \frac{1}{E} \frac{2r_1^2}{r_2^2 - r_1^2} . \tag{8}$$

Radial deformation of barrel $u$ (m):

$$u = \varepsilon_t r \tag{9}$$

The calculated values of relative tangential deformation of the external surface of the barrel:

- Place (1), $y$ = 11 mm in CSYS 0: $\varepsilon_{t2}$ = 76.16 µm/m
- Place (2), $y$ = 194 mm in CSYS 0: $\varepsilon_{t2}$ = 107.42 µm/m

The calculated values of relative tangential strain are smaller than the measured ones with respect to real dynamic load [1, 2, 7]. The dynamic case will be solved during the course of the next project.

Relative elastic tangential deformation $\varepsilon_{t2}$ (µm/m) in the wall of the FEM model and the relative elastic deformation $\varepsilon_{t2}$, $\varepsilon_{r2}$, $\varepsilon_{a2}$, (µm/m) of the external surface of the barrel are shown in Fig. 8.

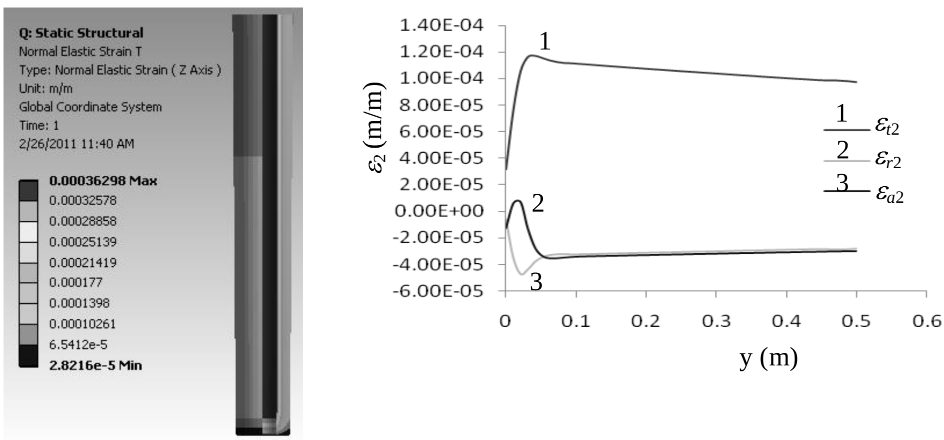


*Fig. 8 Relative elastic deformation of muzzle part (loaded by gas pressure)*
*Left – relative tangential deformation- process in FEM model*
*Right – relative deformation of external surface of the muzzle part of the barrel*

Calculation of elastic radial deformation of the bore: process of elastic radial deformation of barrel is shown in Fig. 9:

$u$ = 4.254 µm where $y$ = 11 mm from muzzle,
$u_{max}$ = 5.809 µm where $y$ = 41.5 mm from muzzle,
$u_{min}$ = 1.36 µm at muzzle ($y$ = 0).

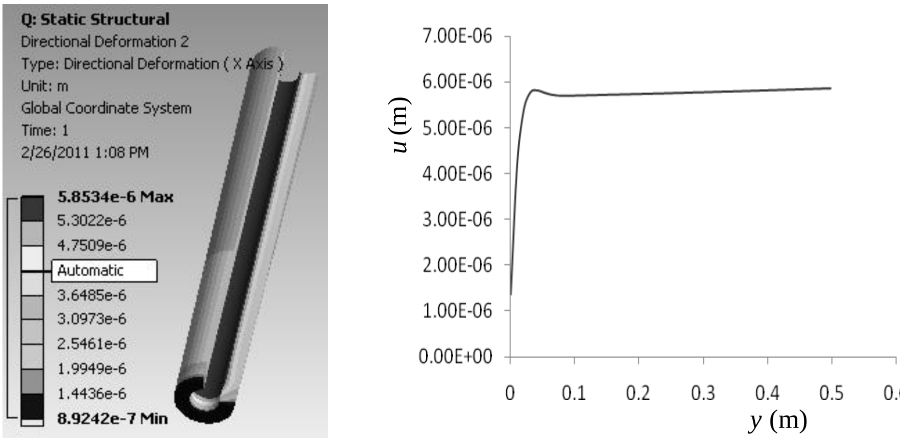


*Fig. 9 Radial elastic deformation load of bore by gas pressure, muzzle of the barrel*

### *3.2. FEM Calculation of Elastic Deformation of Barrel Muzzle Part under Load by Temperature Field and by Gas Pressure*

The rates are investigated for steady and transitional temperature regimes. There are two boundary conditions that occur during shot. All other temperature conditions belong to them. During calculating, the principle of superposition is expected. It means that the contribution of model deformation in a given location and direction, calculated separately for load and temperature, may be aggregated.

There are following temperature regimes:

- **Stationary temperature regime** (Fig. 10; 1 and 2):

It is generated by intense prolonged shooting, in which the balance of the heat taken by borehole from the hot gases equilibrates with the amount of heat to the surroundings by external surface of the barrel. In this case, the whole section of the barrel is considerably heated. The limit temperature value of bore and external surface of the barrel has been known as respective temperature gradient between them. When the temperature in the wall of the barrel exceeds the limit temperature, there is a significant deterioration in the durability and accuracy of the barrel. The specified thermal boundary conditions of both internal and external surfaces of the model are especially close to the allowed values with respect to practice and type of used weapon. The assumed temperature gradient is between 65 °C to 120 °C, proportional to the wall thickness of the barrel.

The specified material and thermal constants of barrel steel:

| | |
|---|---|
| the coefficient of linear thermal expansion $\alpha_1$ | $1.2 \times 10^{-5}$ $K^{-1}$, |
| the isotropic thermal conductivity $\lambda$ | 50 W $m^{-1}$ $K^{-1}$, |
| the reference temperature | 20 °C, |
| the temperature of bore | 320 °C, |
| the temperature of external surface of the barrel | 208 °C. |

- **Transitional temperature regime** (Fig. 10; 3):

Temperature and strain rates on a transient temperature regime are solved for heating from a single shot. In a single shot [3] there is a short-term contact heating surface of the bore to the value 969 °C. Thermal stress of the bore is shown in Table 1. It was found by the experiment [3] measuring the quantities of heat in the barrel of a universal machine gun. Bore surface temperature has plummeted with time, while only narrowly bounded radial bore is heated.

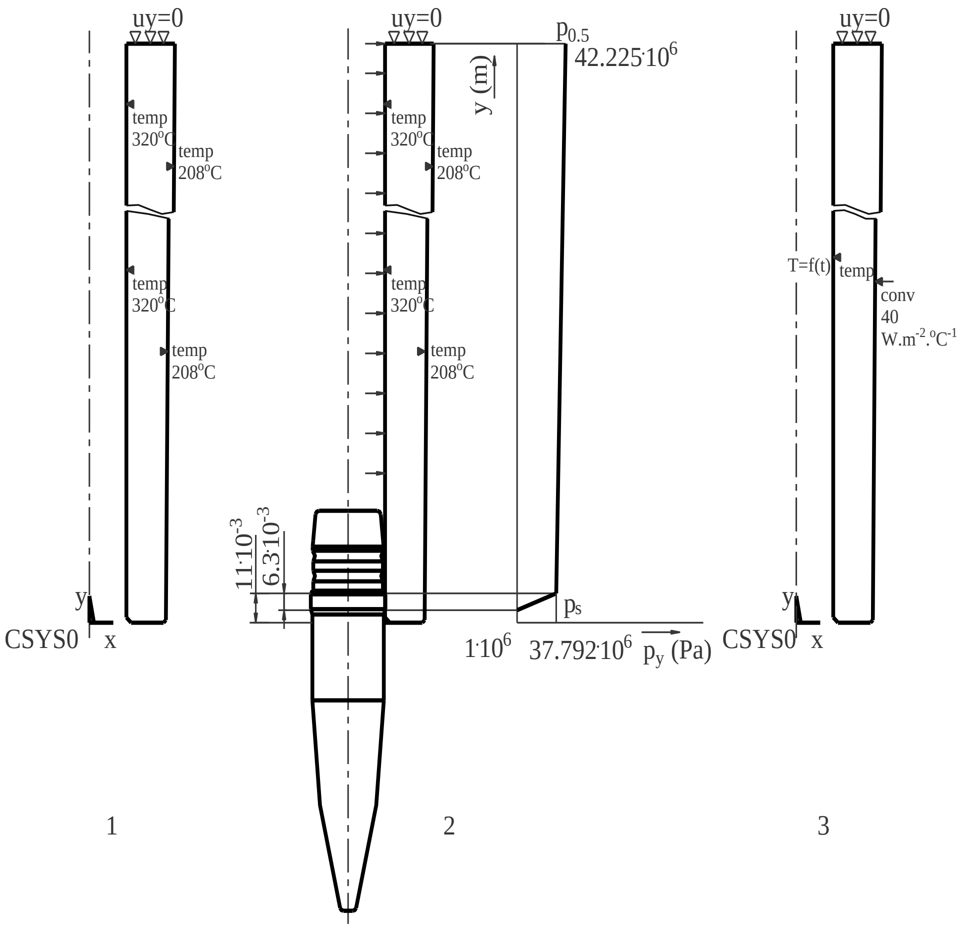


*Fig. 10 Geometry model of barrel muzzle and conditions for solution temperature tasks*

The experiment results about the process of temperature changes in the barrel wall were used according to literature [3]. The barrel wall was heated by a single shot.

The solution is made for thermal load for the duration of heating from $t = 0$ s to $t = 3$ ms. In this period, temperature of the bore surface goes down from 969 °C to 290 °C. Active time of temperature is given simultaneously to the interior bore of the muzzle of the model. The external surface of barrel is given the ambient heat transfer by convection.

*Tab. 1 Temperature process in the wall of the barrel when heated by a single shot* [3]

| r (mm) / t (ms) | 0 | 0.3 | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 | 2.1 | 2.4 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 969 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| 1.5 | 570 | 177 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| 3 | 290 | 216 | 45 | 18 | 18 | 18 | 18 | 18 | 18 |
| 4.5 | 187 | 200 | 69 | 23 | 18 | 18 | 18 | 18 | 18 |
| 6 | 122 | 176 | 83 | 30 | 19 | 18 | 18 | 18 | 18 |
| 7.5 | 95 | 152 | 90 | 37 | 21 | 18 | 18 | 18 | 18 |

where: $t$ is the heat active time on the barrel,
$r$ is the radial thickness of the heated layer of the barrel.
Thermal conditions of the bore (change of the temperature according to time):

function = 969 – 226333 · {TIME} (°C; s)

The specified material and thermal constants of the barrel steel:

the coefficient of linear thermal expansion $\alpha_1$ $1.2 \times 10^{-5}$ K$^{-1}$,
the isotropic thermal conductivity $\lambda$ 50 W m$^{-1}$ K$^{-1}$,
the reference temperature 20 °C,
the steel density $\rho$ 7850 kg m$^{-3}$,
the specific heat capacity $c$ 510 J kg$^{-1}$ K$^{-1}$,
the specific heat permeability of the external surface $k$ 40 W m$^{-2}$ K$^{-1}$.

Calculated results of temperature fields and radial deformations:

Steady temperature regime and static pressure systems: Distribution of radial temperature field in the wall of the barrel has an exponential process (Fig. 11).

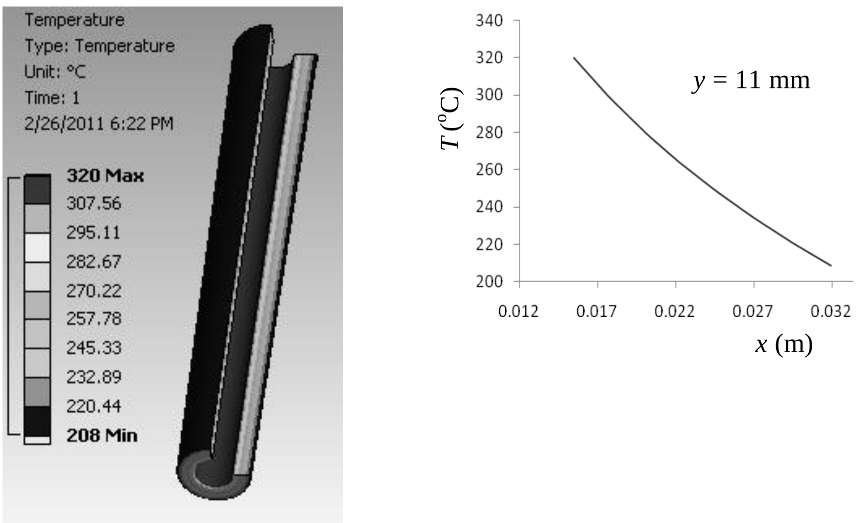


*Fig. 11 Thermal field-steady temperature regime, muzzle of the barrel*

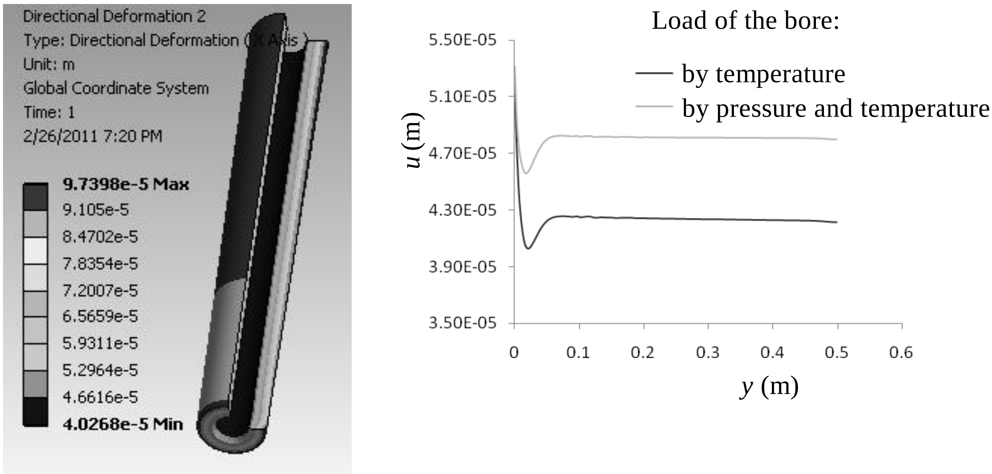


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*Fig. 12 Radial deformation - steady temperature regime, muzzle of the barrel*
*1 – temperature radial dilatation FEM model; 2 – course of radial deformation of the barrel bore*

Calculation gives:

the radial deformation of the bore from pressure of propellant gases: $u = 4.254$ μm,
the radial deformation of the bore from the thermal loading $u = 41.81$ μm,
the radial deformation of the bore from pressure-thermal loading: $u = 46.06$ μm.

Transitional temperature regime:

Solutions for time $t = 0$ to $t = 3$ ms show the parameters for the two periods of heating: $t = 0.1$ ms and $t = 3$ ms. In the observed time of heating, the temperature of the bore drops, but the width of the thermally affected zone in the wall of the barrel increases. For time $t = 0.1$ ms, the thermally affected area is around 0.4 mm. For time $t = 3$ ms, it has a depth of approximately 1 mm.

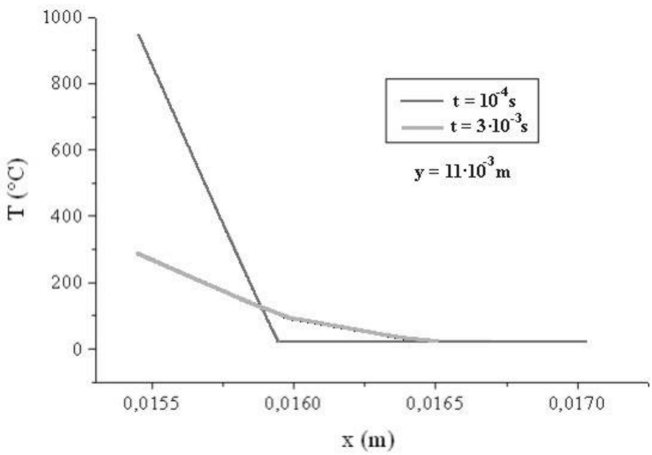


*Fig. 13 Field of temperature in the barrel wall T(x) – transitional temperature regime, y = 11 mm from muzzle of the barrel, x is the depth of the heated area from the bore*

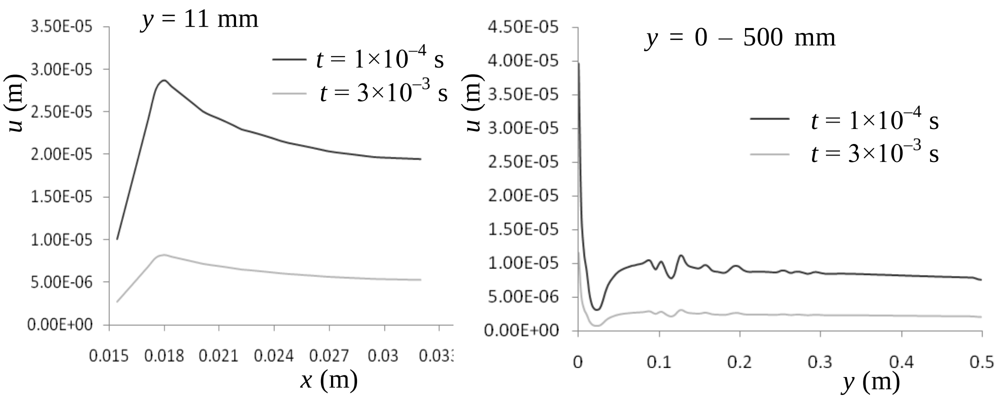


*Fig. 14 Radial deformation (u) - transitional temperature regime, muzzle of the barrel*
*Left – course of deformation in the wall of the barrel for y = 11 mm from muzzle*
*Right – course of deformation along the bore (from muzzle)*

The higher the bore surface temperature during firing, the greater the rate of wear, greater radial deformation and greater deflection of the barrel. Thus when heating the muzzle to permissible temperature, the accuracy of fire decreases.

## Conclusion

The task "Differences of the barrel chamber and muzzle deformation during the shot" can be solved by means of software ANSYS Workbench by FEM. Its results are elastic radial deformation of the bore and the external surface, elastic strain and stress of the barrel at chamber and muzzle and the field of temperature in the barrel wall. High temperature of the barrel wall affects the barrel deformation more than the mechanical load. Maximum temperature of the barrel wall (near of the bore) is kept by the fire regime bellow approximately 350 °C. The temperature decline in the barrel wall is approximately 150 °C, when stabilized temperature regime is adjusted. Impact temperature of the bore surface is approx. 900 – 1000 °C. The expansion of the bore diameter at stabilized temperature regime can be up to 0.06 mm at a calibre of 30 mm and 0.35 mm at a calibre of 125 mm. The expansion of the bore diameter causes greater outflow of the hot propellant gases and it exerts influence on the bore wear at the muzzle part. To sum up, the outflow of the hot propellant gases is determined by the shape of the barrel muzzle when the projectile leaves the barrel and it is increased by the temperature dilatation. The length of this part is approximately three calibres from the muzzle.

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