19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

GUN BARREL EROSION: STUDY OF THERMALLY INSULATING LAYERS

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The heat transfer related to thermal erosion has been simulated using Reynolds' analogy (postulate of an analogy between heat and momentum transfer). The roughness of the inner surface is a key parameter of the model. To take into account the steep gradients of temperature induced by the use of silicon dioxide as a protective material it is necessary to use temperature-dependent thermal diffusivity and conductivity. In accordance with the experiments the model permits to show that the layer can limit the temperature elevation in the steel. There is no risk of fouling because if the layer grows too much, its surface temperature reaches the melting temperature of the material and the excess material is blown away.

INTRODUCTION

High surface temperature on the inner side of a gun tube associated with the abrasive effect of the moving projectile can lead to an amplified erosion which in a high-power weapon system results in an unacceptable reduction of the life duration of the tube.

There are two ways of reducing this thermal erosion:

- in the first one the tube is coated with a refractory metal which can sustain the thermomechanical stress (chromium coating in operational systems);
- the second has a direct influence on the heat transfer to the wall:
  - either on the tube side by using adapted multilayer coatings,
  - or on the gas side by using a modified propellant or a wear-reducing additive.

This paper deals with the modeling of the latter method. In [ ] it is shown that a deposit of silicon dioxide can be obtained on the inner wall of a gun tube. It has been considered desirable to have a model to explain the results. Based on experimental findings the tube is described as a layer of silicon dioxide deposited over the steel part of the gun.

MODELING

Our purpose is to simulate accurately and simply the heat transfer from the gas to the tube in order to be able to perform parametric calculations. For the sake of simplicity the ballistic part of the calculation is based on IBHVG2 [ ]. IBHVG2 provides us at each instant with the following properties necessary for the heat transfer estimation:

- V_{proj}: velocity of the projectile
- P_{mean}: mean gas pressure in the tube
- T_{mean}: mean gas temperature in the tube

The gun is described by the volume of the combustion chamber, its equivalent length l_0, the length of the bore, the diameter of the bore D. As there is no erosion in the combustion chamber, only the heat transfer to the tube will be simulated.

Modeling the Heat Transfer from the Gas to the Wall

Our aim is to calculate the heat transfer which is given by the formula (1).

$$q = h(T_G - T_W) = \lambda \frac{\partial T}{\partial r} \qquad (1)$$

with:	h:	inner wall heat transfer coefficient	(W/m^2·K)
	λ:	thermal conductivity of the tube	(W/m·K)
	T_G, T_W:	temperature of the gas, of the tube	(K)
	T:	temperature inside the tube	(K)
	r:	radial position in the tube	(m)

Using Reynolds' analogy which states that the heat and momentum transfers are performed by the same particles we can write:

$$\frac{h}{\rho C_P V_m} = \frac{\tau_p}{\rho V_m^2} = f/2 \qquad (2)$$

with:	ρ:	gas density	(kg/m^3)
	C_p:	specific heat of the gas	(J/kg)
	V_m:	gas velocity	(m/s)
	$f/2$:	friction factor	(dimensionless)
	τ_p:	strain at the wall	(kg/m·s^2)

Equation (2) gives:

$$h = (f/2)\rho C_P V_m \qquad (3)$$

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Equation (3) can be expressed in variables which are found more currently in the domain of interior ballistics. ρ can be replaced by $\frac{M}{R}\frac{P_{mean}}{T_{mean}}$, where M is the molecular mass of the gas and R the perfect gas constant. C_P can be replaced by $\frac{R}{M}\frac{\gamma}{\gamma-1}$ (γ is the ratio of specific heats) and the velocity V_m of the gas at any point x in the tube can be calculated as $\frac{l_0+x}{l_0+l}V_{proj}$ (l is the displacement of the projectile).

Thus we obtain:

$$h=(f/2)\frac{\gamma}{\gamma-1}\frac{P_{mean}}{T_{mean}}\frac{l_0+x}{l_0+l}V_{proj} \tag{4}$$

According to this formula it is not surprising to observe serious erosion problems in high-power guns because in this case the product $P_{mean}\,V_{proj}$ is high. Small defects on the inner wall will induce turbulence, i.e. locally increase the friction factor and also the size of the defects.

As will be seen in the next section, the layer obtained in the experiments has a different roughness from that of the raw steel surface, so it is important to take into account the surface roughness when estimating the friction factor *f/2*. The latter depends on the type of flow (laminar, turbulent), on Reynolds' number $Re=\frac{\rho V_m D}{\mu}$ and on the relative roughness $rug/_D$ of the tube. For the flow inside a gun tube Reynolds’ number is always high, in the order of 106 to 108. In these conditions, the friction factor can be calculated using the relation of Churchill given in [3].

$$\frac{1}{\sqrt{f/2}}=2.457\ln\left(\left(\frac{7}{Re}\right)^{0.9}+0.27\frac{rug}{D}\right)^{-1} \tag{5}$$

Simulation of the Heat Transfer in the Tube

The equation governing the heat transfer in a cylindrical geometry is well known. Making the assumption that heat propagates only radially allows us to work with only one space coordinate. We use the following equation:

$$\rho_S C_{Ps}\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) \tag{6}$$

The notations here are:

ρ_S:	density of the solid	(kg/m^3)
C_{Ps}:	specific heat of the solid	(J/kg·K)
t:	time	(s)
a:	thermal diffusivity of the solid	(m^2/s)

Generally, the right-hand term of the equation (6) is derived considering that the heat conductivity is independent of the position. In our case this assumption is no longer valid and we must take into account the variation of the conductivity with the position. One obtains:

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

This equation is solved using a finite difference method for a semi-infinite tube in the radial direction with usual boundary conditions: at the wall, the heat flux is given by equation (1), and at the other end it is equal to zero. At the interface between the layers we assume that the heat fluxes are the same on both sides of the interface and that there is not contact resistance to the heat transfer (the temperature is the same on both sides of the interface).

As an initial condition, a constant temperature of 300 K is assumed all over the barrel.

EXPERIMENTAL RESULTS IN A 20 MM CALIBER GUN

Location ot the Sensors

The series of shots have been fired with a 20 mm laboratory gun which is described in [1]; the pressure inside the chamber has been measured with a Kistler gage. An intermediate insert between the combustion chamber and the tube is fitted with surface probes and temperature sensors [4] to measure the temperature inside the wall. Some other plane surface probes can be fitted at different points along the tube. The position of this insert and of the probes can be seen on Fig. 1.

Experimental Results

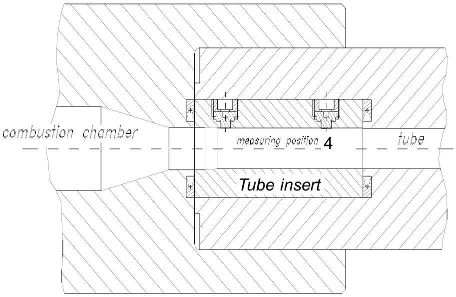

Figure 1: View of the part of the gun containing the tube insert.

A first series of shots using a Nena-G4 propellant (63% NC, 35% DINA, 2% Aerosil 300) prepared at ISL has shown the following facts:

- the surfaces of the surface probes and of the insert are covered with a well-adhesive layer;
- there is no significant variation in the layer thickness with the number of shots (from 2 to 10);
- the thickness of the silicon oxide layer is approximately 10 mm on the insert surface and the layer is somewhat thinner on the surface probes;
- the thickness of the layer decreases with the distance, but the tube can still be covered at a distance of 50 calibers.

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An example of layers obtained in the tube insert after 10 shots is shown in Fig. 2.

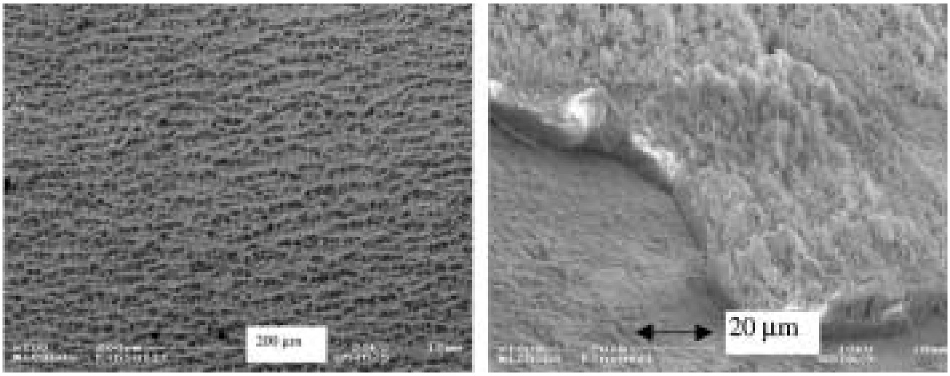
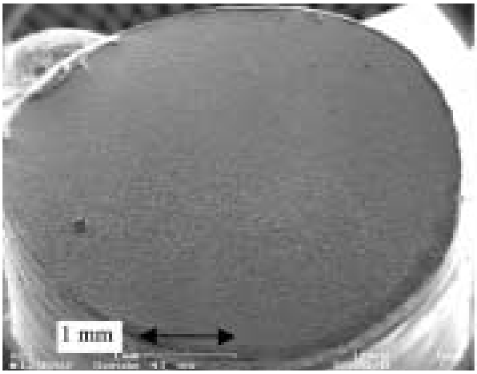


Figure 2: Layer obtained with Aerosil included in G4 propellant.

Another series of shots has been performed with a very high burning temperature GB Pa 125 propellant and Aerosil has been added as a separate part of the propelling charge. The coatings obtained are smoother than for the shots with G4 propellant. This can be seen on Fig. 3, which was made after 3 shots.



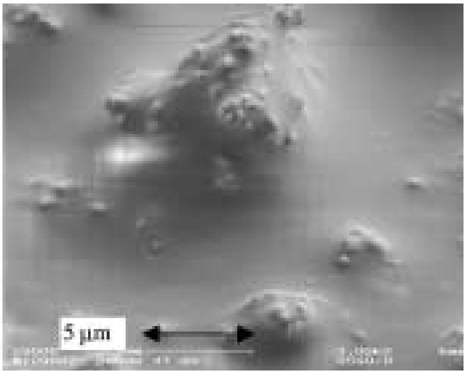


Figure 3a: Surface after 3 shots.

Figure 3b: Magnification of Fig. 3a.

SIMULATION RESULTS

Thermal Properties of Steel and Coating

As was said previously it is necessary to take into account the variation of the thermal conductivity and diffusivity with temperature. For both materials the density is considered to be a constant. Only the conductivity, the specific heat and the resulting diffusivity are considered to be dependent on temperature. The thermal properties are taken from [5] for the specific heat and from [6] for the thermal conductivity.

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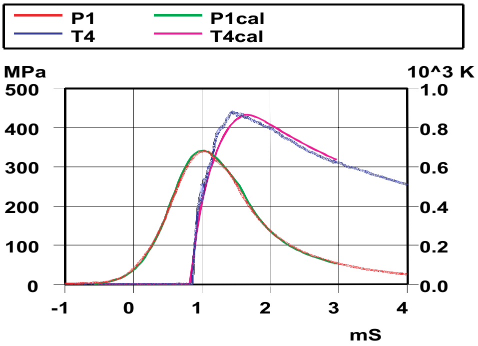
Simulation without any Coating

On Fig. 4, a comparison is shown between measured and calculated results. The pressure in the chamber is calculated with IBHVG2, for a shot with the 20 mm gun. The projectile mass is 122 g and 50 g of GB Pa 125 French propellant are used without an additive; the initial velocity is 1085 m/s. The temperature at measuring point No. 4, at 72 mm from the forcing cone is calculated from the results of IBHVG2 with our simulation. The roughness of the steel tube is set to 0.2 µm. It can be seen that the maximum temperatures are in good agreement with each other. The slopes of the temperature curves after a maximun has been reached are also consistent with each other.

Simulation with a Coating of Silicon Dioxide

Firstly, the heat transfer model is applied to a tube coated with the measured thickness of silicon dioxide in order to check if the simulation can be a reasonable description of the reality. The simulation refers to an experiment with 50 g of GB Pa 125 propellant carried out at the end of a series of 10 shots. At this stage of the experiment the tube insert is coated with a layer of 10 mm of silicon dioxide and the roughness is clearly higher than for steel. It is estimated to be 0.5 µm. The curves of Fig. 5 show that the temperature at the location of the temperature sensor is reduced by approximately 120 K compared to the case with no protective layer. The temperature at the steel surface is reduced by 150 K.



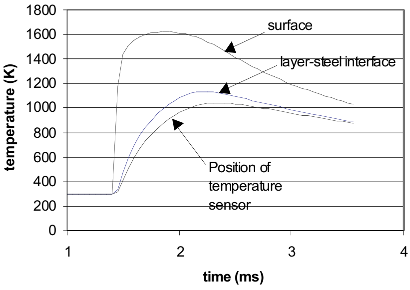


Figure 4: Comparison between.
- measured and calculated pressures.
- measured and calculated temperature increase.

Figure 5 : Temperature calculated for a layer of 10 µm thickness.

Secondly, calculations are made with different thicknesses of coating material, in order to determine the maximum thickness obtainable. If Aerosil is used as an additive, every shot will deposit a thin layer of material. From shot to shot the thickness will increase until the surface temperature reaches the melting temperature of silicon dioxide, and then the thickness of the layer will remain constant, as no more additive can be deposited. For silicon dioxide the melting temperature is approximately 1880 K. Fig. 6 shows that the surface temperature increases when the thickness of the layer increases. For a thick-

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ness of 25 μm the surface temperature is 1880 K, which demonstrates that the layer cannot grow for ever. Fig. 7 shows the interface temperature for different thicknesses. It is clear that the insulating effect increases at the same time as the thickness.

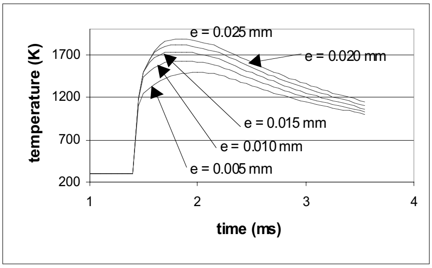

Figure 6: Surface temperature for different thicknesses of coating.

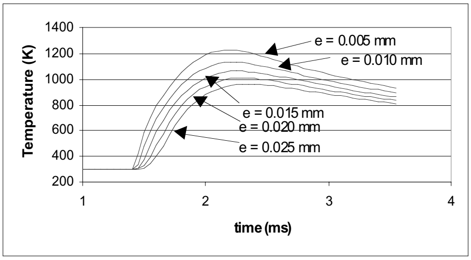

Figure 7: Temperature at the interface for different thicknesses of coating.

CONCLUSION

A simple model of heat transfer has been built based on correlations from the domain of fluid mechanics. This model can be correlated with temperature measurements in a gun. Using silicon dioxide as an additive allows to reduce the steel temperature by approximately 150 K.

Acknowledgements

The authors would like to thank Mrs Braun for preparing the G4 propellant, Mr Zettler for performing the series of shots, Mr Lichtenberger for the SEM images and Mr Mura and Raupp for doing some drawings.

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