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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN A 120 MM TESTING GUN BARREL BASED ON A SPACE MARCHING FINITE DIFFERENCE ALGORITHM FOR THE INVERSE CONDUCTION METHOD

D. Boisson[1], G. Légeret[1], JF. Barthélémy[2]

[1] *Giat Industries, Division des Systèmes d'Armes et de Munitions, Département Balistique Intérieure et Aérobalistique, 7, Route de Guérry, 18023 Bourges Cedex, France*
[2] *DGA, ETBS, DCE, Route de Guérry, BP 712, 18015 Bourges Cédex, France*

Frictional, convective and radiation heating knowledge is important when attempting to understand the degradation mechanisms of the 120 mm gun barrel inner wall. Bore surface temperature and heat transferred to the 120 mm chromium testing gun tube with APFS_DS (without and with additives in the propellant powder) can be experimentally determined by applying an inverse heat conduction method on temperature measurements obtained at different depths in the gun barrel. Here, the gun tube involves fifteen seating, distributed in three sections along its length. We used a very high frequency ultrasonic sensor inside the tube to help the machining and to measure the thickness with an accuracy of +/– 10 micrometers. The total input flux is determined then validated and its maximum values range from about 1 GW/m^2 to 300 MW/m^2. The maximum inner wall, the chromium steel/interface temperature and the thermal efficiency of additives are also determined. This latest is an interesting result. Next step of our work will concern the validation of the MECCAD code.

INTRODUCTION

During the shot, the inner wall of the barrel receives the total thermal flux resulting from the combustion of the propellant charge and from the friction of the projectile. The knowledge of this flux is very important for wear problems in gun barrels because it governs the whole thermal behaviour of the barrel and for thermo mechanical calculation codes. But, direct calculations and direct measurements of this flux are quite difficult (high gas pressure, very fast dynamic, ...). Today the more reliable way to determine the total thermal flux, the inner wall and the interface temperatures consists of temporal measurements of the temperature inside the tube associated with an inverse conduction finite difference method. In the past, we validated this experimental method for the medium calibre guns.

Here, we are interesting in using this experimental method for the 120 mm chromium testing gun tube with APFS_DS with and without wear reduce additives in the propellant charge. Once we validated the experimental fluxes, the thermal efficiency of APFS_DS with additives is determined.

In this paper we will also look after the gas discharge calculation (when the projectile moves in the barrel) and compare with gas pressures measured along the barrel.

PRESSURE AND TEMPERATURE MEASUREMENTS IN A 120 MM CALIBRE CHROMIUM TESTING GUN TUBE

Sensors location

Five pressure sensors (piezoelectric ones) are located respectively at 80, 470, 1025, 2750 and 5000 mm from the breech.

Internal temperatures were measured using intrinsic iron/constantan and chromel/alumel thermoelectric sensors. This measurement procedure presents a very short response time and is validated for medium calibre guns: see [1, 2, 3 and 4].

The gun barrel involves fifteen seating, distributed in three sections along its length. The axial locations are respectively near the forcing cone (1300 mm from the breech), the middle (4200 mm from the breech) and near the end of the tube (6120 mm from the breech). Due to the very steep temperature gradients existing near the inner surface of the gun barrel, the measuring holes are drilled as to set the sensors at the shortest distance from his surface. For each cross section we need three thermocouples located at three depths: for inverse conduction calculation method only two depths are used, the third depth which is the farthest from the inner wall is used for validation tests. Upstream sensors should be the nearest as possible from the inner surface of the gun barrel. The closest distances that could be practically located without destruction due to internal pressure are respectively 630, 370 and 270 micrometers with an accuracy of +/–10 micrometers. For holes machining help and thickness knowledge, we used a very high frequency ultrasonic sensor inside the tube: see Fig. 1.

The thermoelectric sensors are constituted by 0.25 mm diameter constantan wires welded at the bottom of a 1.65 mm diameter flat bottom hole [1]. A precision Teflon guide is used to ensure that the measuring wires are located exactly in the centre of the drilled holes. The steel-constantan junction is obtained by using a capacitor discharge technique. Once the welding is assured, the guide is retired and replaced by glue. The iron wire is welded at the outer surface of the tube. This thermoelectric sensor power is about 52 µV/°C, if we don't consider the iron-steel parasite couple during the shot.

Studies realized at Giat Industries have shown that during a gun shot, we under-estimate the barrel temperature (when the initial tube temperature value is about the ambient temperature) with this BRL's technology. So, in addition, two chromel/alumel thermoelectric sensors have been tested and the two 0.25 mm diameter wires are welded at the bottom of the holes. Here, there is no more parasite couple during the gun shot and the measure should be more accurate. Moreover its temperature range is between –200°C to 1250°C, while the constantan/iron temperature ranges between 0 to 700°C.

Data acquisition system

The sampling frequency of the Nicolet data acquisition system used is 10 kHz. It enables the recording of the heating and the cooling phases [5].

Tests conditions [5]

The tests were carried out at ETBS on February 1999, on a 120 mm calibre testing gun barrel. The tube length is about 6 meters. The inner surface of this tube is protected by a chromium coating. There was no wear on this tube before the tests. The shots were realized with inert APFS_DS of about 7 kg (without and with 230 gr of wear reduce additives in the propellant charge). We used double propellant charges.

During the tests, which are usually reproducible, we saw:

- breakings of some thermocouples caused by vibrations, by the muzzle break blow,
- thermocouple signals perturbed by the 50 Hz local circuit supply frequencies, ...
- chromel/alumel sensor signals too small because of too large wires diameters.

One part of Fig. 4 and 5 show the numerically filtered (smoothing method) temperatures measured in the section near the end of the tube with APFS_DS respectively without and with additives.

First analysis of the wear reduce additives efficiency

The additives are located at the top of the charge. The analysis of the temperature measurements shows us a good thermal efficiency of ammunitions with additives and with a small decrease of the gun performances (the maximal value of the projectile velocity decrease is about 1.25%).

The temperature decreases are between:

- 3% to 4% in section near the forcing cone,
- 11% to 13% in section near the middle of the tube,
- 5% to 9% in section near the end of the tube.

DETERMINATION OF THE TOTAL INPUT FLUX BY USING AN INVERSE HEAT CONDUCTION METHOD AND VALIDATION

Bore surface temperature and heat transferred to the gun tube can be experimentally determined by applying an inverse conduction method on temperature measurements obtained previously.

Principle of Raynaud and Bransier inverse heat conduction method [6]

It's commonly assumed that, for transient phenomena, the axial heat transfer is negligible versus the radial one: see [7]. In these conditions, a non linear unidirectional space marching inverse conduction finite-difference algorithm derived from Raynaud & Bransier [6] and adapted to cylindrical coordinates can be applied to determine the heat fluxes incoming to the barrel interior wall from thermographs recorded. We also consider that the heat transfer is axisymmetrical: all the sensors at the same depth in a section, receive the same heat flux.

First, a direct calculation using an implicit scheme is realized between the two sensors (upstream and downstream) and we determine the flux near the upstream sensor. The inverse calculation (explicit scheme) has got a space progression and is then realized between the upstream sensor and the inner wall to determine the temperature field in this area. Finally, the total input heat flux is calculated from an energy balance on the half-mesh of the cross surface area.

The space meshes are identical in the direct and the inverse area. The time stop used for the calculation is a multiple of the acquisition time step, to avoid interpolations between the recorded temperatures. The time step is chosen as to respect this criteria [8]:

$$\Delta t^* = a.\Delta t/E^2 > 0.01 \tag{1}$$

where: Δt^*, is the adimensional time step
Δt, is the time step (s)
a, is the material diffusivity (m^2/s)
E, is the distance between the inner surface and the upstream sensor (m).

The choice of the space step is also important if we want a stabilised inversion. This latest is chosen as to respect the "mesh Fourier number":

$$M= a.\Delta t/\Delta r^2 > 1 \tag{2}$$

where Δr is the space step (m).

If $10^{-3} < \Delta t^* < 10^{-2}$, the inverse calculation is possible but we need recorded thermographs without noises and/or little space steps, but anyway we obtain a reduce flux with a slower dynamic.

The reliability of this method is also depending on the accuracy of different entrance data [2]:

- thermal properties of the material in which the sensors are embedded and of the chromium coating,
- location of the sensors (we used an ultrasonic sensor): see paragraph before,
- thermometry problems (thermoelectric power determination, signal disturbances).

Determination of the total heat flux entering the inner wall of the 120 mm chromium testing gun tube with APFS_DS

The total input heat flux is determined and its maximum values range from about 1 GW/m^2 to 300 MW/m^2, respectively from the forcing cone to the end of the tube. Fig. 2 shows the total heat flux entering the inner wall versus the time, near the end of the tube.

Its maximum valne for the APFS_DS without additives is about 270 MW/m^2 with a slop up time of about 3 ms. The numerical conditions of the calculation are $\Delta r = 10\ \mu m$ and $\Delta t = 1{,}5.10^{-4}$s, so in this cross area $\Delta t^* = 0.065$ and M ~13.

For the APFS_DS with additives, we calculated the flux with the same numerical conditions.

So it is possible to determine the thermal additive efficiency.

Fig. 3 shows the inner wall temperature and the chromium/steel interface temperature neat the end of the tube, for the APFS_DS without and with additives. Once these results validated (next paragraph) we could discuss of these ones and evaluate the thermal efficiency of the additives we used.

Validations

Validation tests are carried out: the total input fluxes are used as boundary conditions of a direct calculation code names THETA1D2D [7]. This code calculates the temperatures at any point of the barrel and at any time of the simulation. The measurement/calculation comparisons are satisfying: see Fig. 4 & 5. And this validation is absolute when the measurement/calculation comparison is correct for the sensor the farthest from the inner wall (which is located out of the inverse calculation area).

Fig. 4 & 5 show the results at the three depths of the comparison realized in the cross area located near the end of the tube:

- there is little differences during the slop up time of the temperatures,
- these differences increase during the cooling phase; it’s because during the inverse calculation, in this phase, the fluxes are positively disturbed. In fact the numerical parameters are optimised for the heating phase (fast dynamic) and not for the cooling phase. If we reduce this non physical noise we validate the inverse method during the cooling phase.

For the APFS_DS without additives in this section, the maximum inner wall temperature value is about 1100°C. We are below the melting temperature of the chromium. The maximum interface temperature value is about 860°C and its application time is greater. We are above the steel structural transformation temperature.

Second analysis of the additives thermal efficiency

Fig. 2 and 3 have shown the thermal of ammunition with additives in the propellant charge. This is an interesting result which is not accessible by direct measurements and/or by an interior ballistic calculation code. In the cross section near the end of the tube, additives reduce the inner wall maximum temperature value of about 250°; and the gun performances are quite the same. The projectile velocity decrease is about 1%. In the others cross sections the efficiency is also important: the maximum temperature decrease is about 150° in the section near the forcing cone.

COMPARISON WITH DIRECT FLUX CALCULATIONS: THE MECCAD CODE [3 and 4]

It's now possible to validate the MECCAD code [4] for the 120 mm gun, so for large calibre guns with ammunitions without additives.

The MECCAD code enables us to calculate the gas discharge and the heat exchanges occurring in a gun barrel when the projectile moves in the tube and after it leaves the barrel. And so it enables us to describe the thermal behaviour of a gun during the shot and/or a burst.

First of all we have to compare the gas discharge (Pgas, ...) calculated by a numerical interior ballistic code (1D, 2 phases) with the one measured: five pressure sensors were used. Fig. 6 shows this comparison between calculations and experiments (when the projectile moves inside the barrel): we can see three maximum gas pressures measured along the barrel and the gas pressure field calculated. We observe a difference which is more important when we are nearer the end of the tube. Here the difference is about 250 bars.

So before going further in our comparison we have to be more accurate in the calculation of the gas discharge. We have to take into account in the interior ballistic code the gas thermodynamic properties variability with the gas temperature and pressure, if possible. This work will be done soon.

CONCLUSION

The inner wall chromium and the interface temperatures as well as the heat transferred to the 120 mm chromium gun tube testing with APFS_DS (without and with additives in the propellant charge) is determined by measuring the temperature evolution at different depths along the barrel and applying a mono directional non linear inverse heat conduction algorithm on these temperature measurements. The maximum input flux values range from about 1 GW/m^2 to 300 MW/m^2.

This study shows us:

- the know-how of temperature measurements, thus of holes machining with an accuracy of +/–10 micrometers; and of inverse calculations for large calibre guns,
- a method to determine the chromium inner wall temperature efficiency of wear additives. We saw, when we used our additives, that the chromium inner wall temperature decrease is about 150° in a cross area located near the forcing cone.

Next step of our work will concern the validation of the MECCAD code for the 120 mm gun barrel. This code enables us to study the gas discharge and the heat exchanges occurring in a gun barrel during and after the shot. First of all we have to calculate more accurately the interior ballistic gas discharge when the projectile moves in the barrel.

Then overheating and cheaper predictions with MECCAD code will be carried out, for example with the 155 mm calibre gun, where burst fires can induce wear and/or security problems (self ignition of the modular charges).

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REFERENCES

1. T.L. Brosseau, “An experimental method for accurately determining the temperature distribution and the heat transferred in gun barrels”, *BRL Rpt No l740,* 1974
2. J.J. Serra, J.M. Gineste, S. Serror, Y. Guilmard, M. Cantarel, “Experimental investigation of heat transfer in a gun barrel based on a space marching conduction method”, *Inverse Problem On Engineering, Palm Coust, Florida,* June 13–18, 1993
3. D. Boisson, H. Sadat, F. Rigollet, G. Arnaud, C. Grignon “Computation of boundary layers and calculation of parietal heat flux during a shot in a gun barrel”, *15th Int. Symp. On Ballistics, Jerusalem, Israel,* 21–24 May, 1995
4. D. Boisson, R. Cayzac, G. Legeret “Study of the gas discharge and the heat exchanges occurring in a gun barrel after the projectiles leaves the barrel: validation for the 30 mm gun”, *18th Int. Symp. On Ballistics, San Antonio,* USA, 15–19 November, 1999
5. P. Collet, C Freygnac “Mesures de temperatures pariétales et des pressions dans un canon de 120 mm”, *DGA/ETBS/DCE Rpt,* Avril 2000
6. M. Raynaud, J. Bransier “Experimental validation of a new space marching finite difference algorithm for the inverse heat conduction model”, *8th Int. Heat Transfer Conference, San Francisco CA,* 1986
7. D. Boisson, C. Grignon, M. Roux, P. Gillard “1D and 2D thermal modeling of the heating and the cooling of a gun barrel during a burst”, 14th *Int Symp. On Ballistics, Quebec, Canada,* 26–29 Septembre, 1993
8. M. Raynaud, *Techniques de l’lngénieur, Génie Energétique no BE162,* octobre 1997

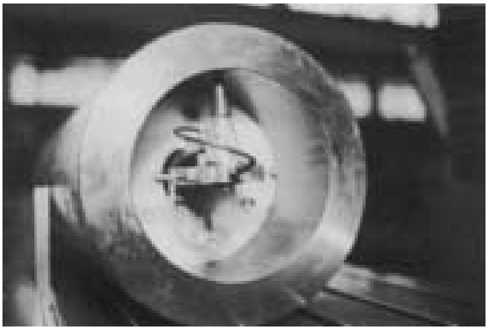

Figure 1: Ultrasonic sensor inside the tube.

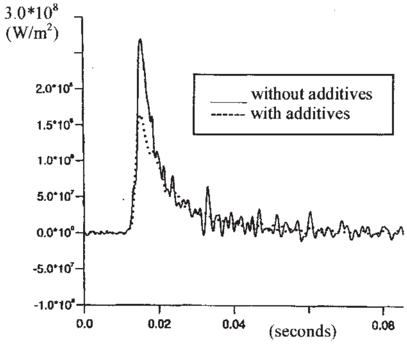

Figure 2: Total input flux entering the muzzle inner wall area.

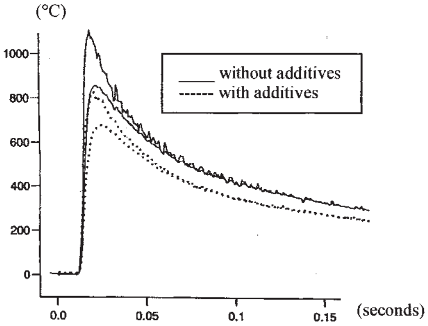

Figure 3: Inner wall and interface additives thermal efficiency.

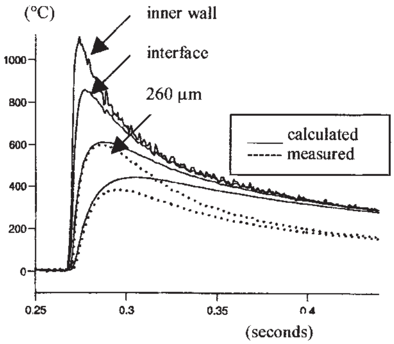

Figure 4: Comparison Tcalculated with Tmeasured near the muzzle.

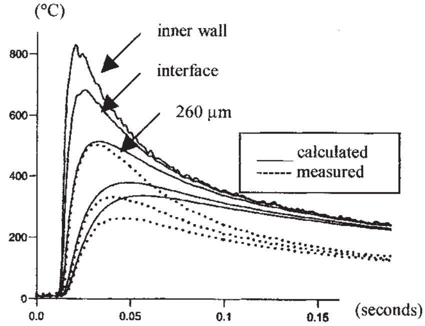

Figure 5: Comparison Tcalculated with Tmeasured near the muzzle (with additives).

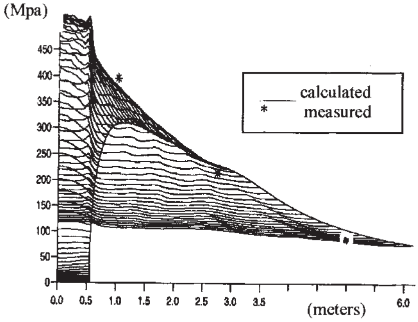

Figure 6: Comparison Pcalculated with Pmeasures along the tube.