



Temperature Sensitivity of Propellant Combustion and Temperature Coefficients of Gun Performance

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Abstract: One of the objectives of gun propellant research is to develop green formulations of gunpowder that should be less temperature sensitive than the current gun propellant. The temperature sensitivity of these new green formulations of the propellant should be measured to identify the less temperature sensitive green formulations. However, there are deficiencies in the methodologies for the measurement of the temperature sensitivity of gun propellants. Therefore, the aim of this investigation was to fill the gap by establishing a method for the measurement of the temperature sensitivity of deterred gun propellants by closed vessel tests. The temperature sensitivity of the burning rate of ball propellants and the temperature coefficients of gun performance were determined using closed vessel tests and ballistic firing, respectively. Specific definitions of temperature sensitivity and temperature coefficients were evaluated. The relation between these parameters has never been explicitly investigated previously. Assessing the temperature sensitivity of propellants by closed vessel tests is of added value to the range of ballistic tests if the results of these tests can be well correlated to the results of ballistic firings. Therefore, a comparison between both parameters was made. A correspondence has been observed between the temperature sensitivity of the propellant burning rate, as obtained from closed vessel tests, and the temperature coefficients as obtained from ballistic firings.

Keywords: firing temperature, temperature sensitivity, temperature coefficient, ball propellant, ageing, ballistic firing, closed vessel tests

1 Introduction

In an effort to supply an environmentally friendly propellant for ammunition applications that also improves the characteristics of insensitive munitions, a project has been initiated as part of a collaboration between the Laboratory of Energetic Materials of the Royale Military Academy of Brussels (Belgium) and PB Clermont (Engis, Belgium). This project covers two topics: the first is the production of a propellant containing no carcinogenic materials (for example, dibutyl phthalate (DBP), currently used as a deterrent or plasticizer in several propellant formulations, is a known carcinogen [1]); the second topic is the fact that this new green propellant should be less temperature sensitive than the current gun propellant.

The temperature sensitivity of these new green formulations of the propellant should be measured to establish their lower temperature sensitivity. However, there are no methodologies for characterizing the temperature sensitivity of gun propellants.

Therefore, the aim of this investigation was to fill this gap and to enrich the range of ballistics tests by establishing a method for the measurement of the temperature sensitivity of deterred gun propellant using a closed vessel test.

The temperature sensitivity is a parameter of the propellant, while the temperature coefficient is a weapon parameter. To determine the effects of temperature on the propellant burning rate and its ballistic properties (maximum pressure inside the weapon and projectile velocity), the temperature sensitivity of the propellant burning rate and the temperature coefficients of the gun performance have been determined by two well-known experimental procedures, namely closed vessel tests and ballistic firings, respectively. Closed vessel tests have the advantage that they can be carried out rapidly and relatively easy. By comparison, ballistic firings require appropriate laboratory conditions and infrastructure. Assessing the temperature sensitivity of the burning rate of the propellants by closed vessel tests will be of added value to the range of ballistic tests if the results of these tests can be well correlated with the results of ballistic firings (temperature coefficients). For this reason, closed vessel tests and firing tests with non-aged and aged spherical and flattened propellants, conditioned at various temperatures before testing, have been performed and the correspondence between temperature sensitivity of the burning rate and temperature coefficient has been studied.

2 Definitions

2.1 Initial temperatures

The initial temperature is T_0 . In the case of closed vessel tests, the initial temperature is the temperature at which the propellant is conditioned before the tests. For ballistic firing, the initial temperature is the temperature at which the cartridges filled with the investigated propellants are conditioned before firing.

2.2 Temperature sensitivity

To define the temperature sensitivity of the burning rate, it is often assumed that, in the traditional Vieille's law, $r_p = b \cdot P^n$, the pressure exponent, n , is not a function of the initial temperature [2]. The temperature sensitivity $\sigma(r_p)$ of the burn rate (r) at a pressure P is thus defined as the relative change in burning rate from the value at 21 °C (benchmark temperature) resulting from a change in the initial temperature dT_0 [2]. The benchmark value of the propellant parameter is set to the value at 21 °C (Equation 1).

$$\sigma(r_p) = \frac{1}{r_p(T_0 = 21^\circ\text{C})} \frac{dr_p}{dT_0} 100 \quad (1)$$

where

- $\sigma(r_p)$ is the temperature sensitivity of the burning rate
- r_p is the burning rate at a pressure P

2.3 Temperature coefficients

The temperature coefficients of a gun are often defined as the relative change (expressed in percentage) of the investigated output ballistic parameters (maximum chamber pressure inside the weapon or projectile velocity) from its benchmark values for a given change of the initial temperature dT_0 [2, 3]. The benchmark values of the ballistic parameters are the ones determined at 21 °C (Equation 2).

$$TC(x) = \frac{1}{x(T_0 = 21^\circ\text{C})} \frac{dx}{dT_0} 100 \quad (2)$$

where

- TC is the temperature coefficient
 - x is the output ballistic parameter (in our investigation, maximum chamber pressure inside the weapon or the projectile velocity)
- We expressed the temperature coefficients as:
- $TC(P)$, the relative change in the maximum chamber pressure compared to

- the value at 21 °C, or
- $TC(v)$, the relative change in projectile velocity.

3 Experimental and Work Programme

The determination of the propellant burning rate was based on closed vessel tests. The maximum pressure inside the cartridge and the projectile velocity were obtained by firing tests using a weapon. All of the tests were performed with propellants conditioned at selected initial temperatures ranging from -54 °C to 71 °C.

3.1 Closed vessel tests

Closed vessel experiments were performed in a vessel of volume 118 cm^3 . The tests were performed at different initial temperatures (-54 , -20 , 21 and 71 °C). Before temperature conditioning, the propellant was placed in a closed glass bottle. This bottle was conditioned for at least 8 h before the test, in an oven for conditioning at higher temperatures or in a Lauda thermostatic bath for conditioning at lower temperatures and then tested immediately, within ≈ 30 s, after being removed from the conditioning cabinet. The closed vessel was loaded with the conditioned propellant at the initial temperature T_0 and the test was accomplished as soon as possible. The test was carried out at ambient temperature, *i.e.* the closed vessel was at ambient temperature and the propellant was at this initial temperature. It was assumed that the temperature change in the propellant during the time between removal from the conditioning facility and ignition of the propellant was negligible. The propellant loading density was 0.15 g/cm^3 . Pressures were recorded using a piezo-electric transducer Kistler 6215. The output voltage of the pressure sensor was transmitted to a data acquisition system at a sampling rate of 250 kHz. The propellant charges were ignited using 1 g of black powder. The black powder ignition system consisted of two electrodes, which were connected with a filament. The latter passed through a bag made of thin plastic filled with black powder. The filament connecting the two electrodes ignited the black powder by the Joule effect, when an electric current was passed.

A typical output from a closed vessel test was the pressure history and, after post-test processing, the burning rate. A computer program provided both the smoothed curve $P = f(t)$ [Gaussian smoothing was used, which is a method of digital smoothing allowing the elimination of the dispersion and oscillations of the pressure time data without affecting the characteristics of the signal (maxima, minima, slope *etc.*)], and calculated its derivative dP/dt .

The burning rate was obtained according to STANAG 4115 by the product of three terms [4]. Two terms are based on the form function and on the differentiation of a modified Nobel-Abel equation, respectively. The last term is the derivative of the pressure obtained as explained above.

3.2 Ballistic firing

The gun firings were performed in an EPVAT (Electronic Pressure Velocity and Action Time) test barrel (5.56 mm × 45 mm) utilizing ammunition containing a lead free primer (Figure 1). A mass of 1.7 g of spherical propellant or 1.6 g of flattened propellant was poured into a drilled standard size (5.56 mm × 45 mm) cartridge. The corresponding loading densities were 0.92 and 0.86 g/cm³. All rounds were fired for four different values of the initial temperature (T_0): -54, -20, 21 and 71 °C. The cartridges filled with propellant were conditioned for a minimum of 14 h and fired immediately, meaning within $\gt 2$ min, after being removed from the conditioning cabinet.

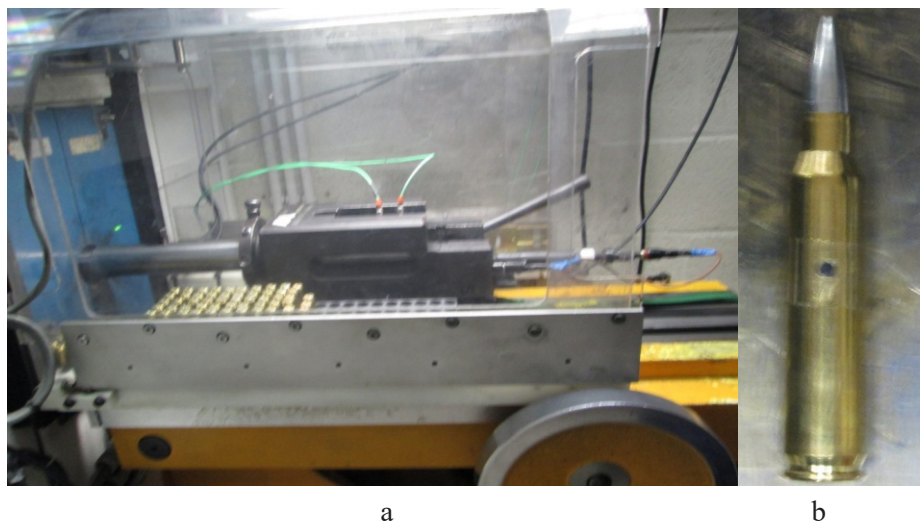


Figure 1. (a) Gun equipped with the piezo-electric transducer Kistler 6215, and (b) pierced cartridge showing the location for the pressure measurement.

3.2.1 Chamber pressure

Piezo-electric pressure transducers Kistler 6215 were used to record the pressure inside the cartridge (Figure 1b, where the hole in the case is visible). The total recording time of the pressure was 4 ms at a sampling rate of 5000 kHz.

3.2.2 Projectile velocity

The projectile velocity at 24 m from the muzzle was also measured. A B471 Precision Light Screen (Figure 2) was placed at a distance of 24 m from the muzzle and determined the projectile velocity by measuring the time (t) required for the projectile to travel a known distance between two infrared sensors (1000 mm \times 600 mm).



Figure 2. B471 Precision Light Screen.

3.3 Ageing plan

All tests were carried out for non-aged propellants as well as for aged propellants, after ageing at 71 °C during 10, 20, and 30 days.

4 Propellants

Ball propellants are used widely in small calibre weapons. Their properties can be adjusted for different ammunition types by changing their particle diameter or by chemically modifying their surface composition by impregnation with a combustion rate modifier called “deterrent”. The deterrent is only present along the surface and up to a certain depth, with an appropriate concentration gradient. The deterred part of the propellant is characterised by a low linear burning rate, while the undeterred part of the propellant is characterised by a high linear burning rate. The deterrent gradient compensates for the decreasing burning surface by an increased burning rate, resulting in a higher performance of the weapon.

A spherical and a flattened deterred propellant were used for this

investigation. The spherical propellant had an average diameter of 553 μm , and contained around 10% of nitroglycerin stabilised with diphenylamine (DPA). The average concentration of the deterrent, dibutyl phthalate (DBP) was 4.8%.

The flattened propellant could be geometrically modelled as an ellipsoid with a major axis of 632 μm and two small axes of 349 μm . It contained around 10% of nitroglycerin and an average DBP content of 4.8%. The two types of propellant differ in their geometry. The compositions of the investigated propellants are given in Table 1 and are almost identical (discrepancies are not significant and the results were within the manufactured tolerance).

For this investigation unaged and aged propellant samples were tested as mentioned in Section 3.3.

Table 1. Composition (wt.%) of the different propellants investigated

Shape	Spherical	Flattened
NC	81.52	82.32
H ₂ O	0.66	0.49
KNO ₃	1.2	0.86
NGL	10.7	10.4
DBP	4.8	4.8
DPA	0.59	0.59
NDPA	0.53	0.54

NC: Nitrocellulose, NGL: Nitroglycerin, DBP: Dibutyl phthalate, DPA: Diphenylamine, NDPA: Nitrodiphenylamine.

5 Results – Spherical Propellant

5.1 Temperature sensitivity

Figure 3 shows the influence of the initial temperature on the curve of the burning rate as a function of pressure. The pressures ranged from 50 MPa to 110 MPa (30% to 70% of the maximum pressure inside the closed vessel, in accordance with the standard procedure STANAG 4115 [4]).

It may be observed that the burning rate decreased with the conditioning temperature of the propellant. The burning rate change was larger towards the higher temperatures (between 71 °C and 21 °C) than towards the lower temperatures (between 21 °C and -54 °C).

As observed in Figure 3 and quantified in Table 2, the temperature sensitivity $\sigma(r_p)$ may be considered constant over the entire range of pressures. This is consistent with the assumption that, in the traditional Vieille's law, $r_p = b \cdot P^n$,

the pressure exponent, n , is not a function of the initial temperature [2]. This corresponds to the assumption that the slope of the $\ln(r)$ vs. $\ln(P)$, resulting from different initial temperatures of the propellant, remains constant. As illustrated in Figure 3, this assumption seems plausible for the propellant investigated.

We may consequently assess that, for the unaged spherical propellant studied, the sensitivity of the burning rate to the initial temperature is equal to:

- 0.305%/°C (towards higher temperatures),
- 0.121%/°C (towards lower temperatures).

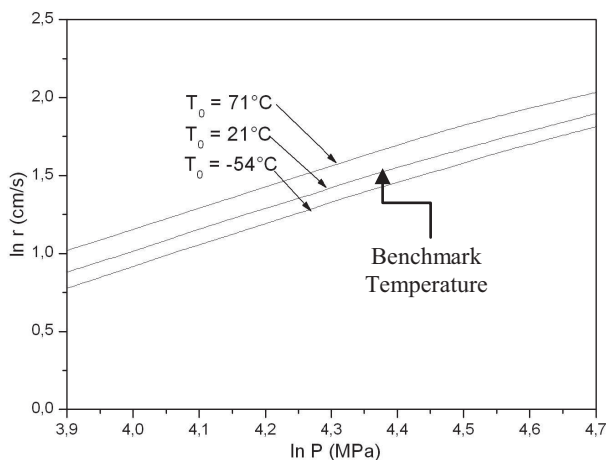


Figure 3. Temperature dependence of the burning rate for the unaged spherical propellant.

Table 2. Values of the temperature sensitivity $\sigma(r_p)$ of the unaged spherical propellant at pressures ranging from 50 MPa to 110 MPa (30% to 70% of the maximum pressure inside the closed vessel). Values in parenthesis are one Standard Deviation (+1SD)

Pressure [MPa]	$\sigma(r_p)$ [%/°C]	
	71 °C/21 °C	21 °C/-54 °C
50	0.287	0.132
60	0.287	0.126
70	0.292	0.120
80	0.310	0.116
90	0.330	0.114
100	0.320	0.117
110	0.309	0.122
Average	0.305 (± 0.016)	0.121 (± 0.006)

5.2 Temperature coefficients

The usual behaviour of the maximum pressure inside the cartridge over the initial temperature range of 70 °C/60 °C to -40 °C/-50 °C is a gradual decrease as the initial temperature decreases [5].

During our investigation, such a monotonous decrease of P_{\max} with the firing temperature was not fully observed, as shown in Figure 4. Instead, two different variations of the maximum pressure inside the weapon as a function of the initial temperature were observed:

- In the range of the higher temperatures (21 °C/71 °C), the maximum pressure inside the cartridge increased as the initial temperature increased. This correlates well with the increasing burning rates, observed in the closed vessel test results.
- Towards the lower temperatures (21 °C/-54 °C), we noticed no significant variation of the maximum pressure.

Figure 4 also shows the variation of the projectile velocity as a function of the initial temperature. The projectile velocity showed a regular decrease as the initial temperature dropped. The decrease in the projectile velocity was larger between 71 °C and 21 °C than between 21 °C and -54 °C.

The temperature coefficients $TC(P)$ and $TC(v)$ over the experimental range of initial temperatures are given in Table 3.

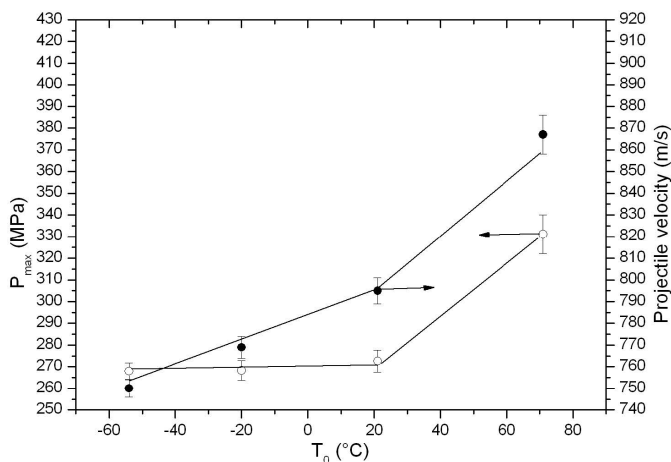


Figure 4. Variation of the maximum pressure inside the cartridges as a function of the conditioning temperature of the cartridge of the unaged spherical propellant (10 shots). The displayed error bars are +1 Standard Deviation (SD). The variation of the projectile velocity is also shown.

Table 3. Values of the temperature coefficients ($TC(P)$) and ($TC(v)$) of the unaged spherical propellant across the experimental range of temperatures 71 °C/–54 °C. The value in parenthesis is one Standard Deviation (+1SD)

TC [%/°C]	Range of temperatures	
	71 °C/21 °C	21 °C/–54 °C
TC (P)	0.429 (± 0.037)	0.022 (± 0.043)
TC (v)	0.177 (± 0.003)	0.075 (± 0.017)

5.3 Ageing of the spherical propellant

As the evolution of the ballistic properties on storage over the year is of major importance, it was of interest to assess the evolution of the temperature sensitivity and temperature coefficients with ageing. For obvious reasons, almost constant values through the year is a basic requirement for high quality propellants. Bearing this in mind, propellants, aged according to the ageing plan in Section 3.3, were tested.

5.3.1 Influence of ageing on the parameters at 21°C

The burning rate of the investigated spherical propellant exhibited no significant variation as a function of ageing, at pressures ranging from 50 MPa to 110 MPa ($T_0 = 21$ °C), as illustrated in Figure 5.

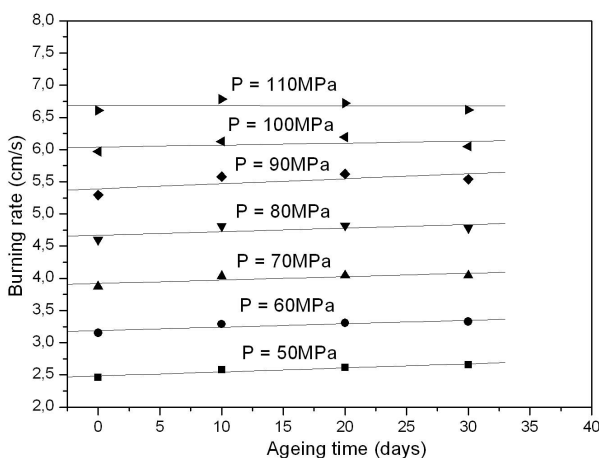


Figure 5. Influence of ageing on the burning rate of the spherical propellant at pressures ranging from 50 MPa to 110 MPa ($T_0 = 21$ °C).

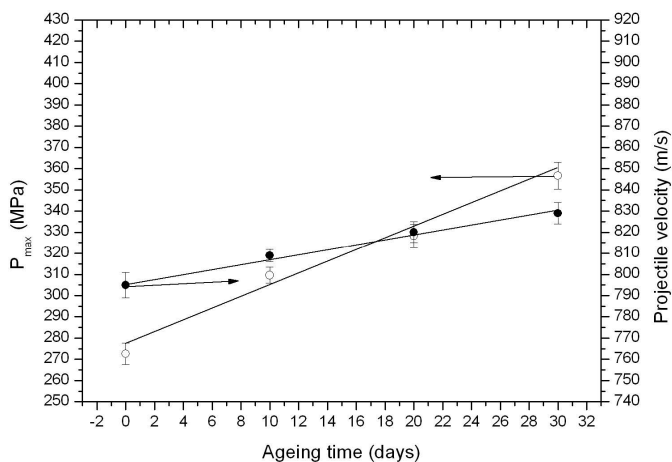


Figure 6. Variation of the pressure inside the cartridge and projectile velocity as a function of the ageing time ($T_0 = 21\text{ }^\circ\text{C}$) for the spherical propellant. The displayed error bars are +1 Standard Deviation (SD).

Figure 6 shows the variation of the maximum pressure inside the cartridge and the projectile velocity as a function of the ageing time (initial firing temperature, $T_0 = 21\text{ }^\circ\text{C}$). The maximum pressure inside the cartridge and the projectile velocity increased with ageing. This is due to the decrease in the burning rate modifier (DBP) concentration at the surface [6]. Previous investigations [7, 8] have shown and explained why the variation of the burning rate (measured by closed vessel tests and standard initiation with black powder) and the maximum chamber pressure and projectile velocity (measured by firing tests) as a function of ageing time do not correlate well. ^{*)}

Table 4. The increase in the maximum pressure inside the cartridge and the projectile velocity of the spherical propellant after ageing (10 to 30 days). Firing temperature was $21\text{ }^\circ\text{C}$

Ageing [days]	P_{\max} [MPa]	v [m/s]
0	273	795
10	310 (+13.7%)	809 (+1.8%)
20	328 (+20.4%)	820 (+ 3.1%)
30	358 (+30.8%)	829 (+4.3%)

^{*)} A better correlation is obtained when using a gas initiation procedure [7, 8].

The magnitude of the increase with ageing in the maximum pressure inside the cartridge and the projectile velocity is illustrated in Table 4. The increase was larger for the maximum pressure; while the change in maximum pressure after 30 days of ageing at 71 °C was +30.8%, the change in projectile velocity was limited to +4.3%.

5.3.2 Influence of ageing on temperature sensitivity and temperature coefficients

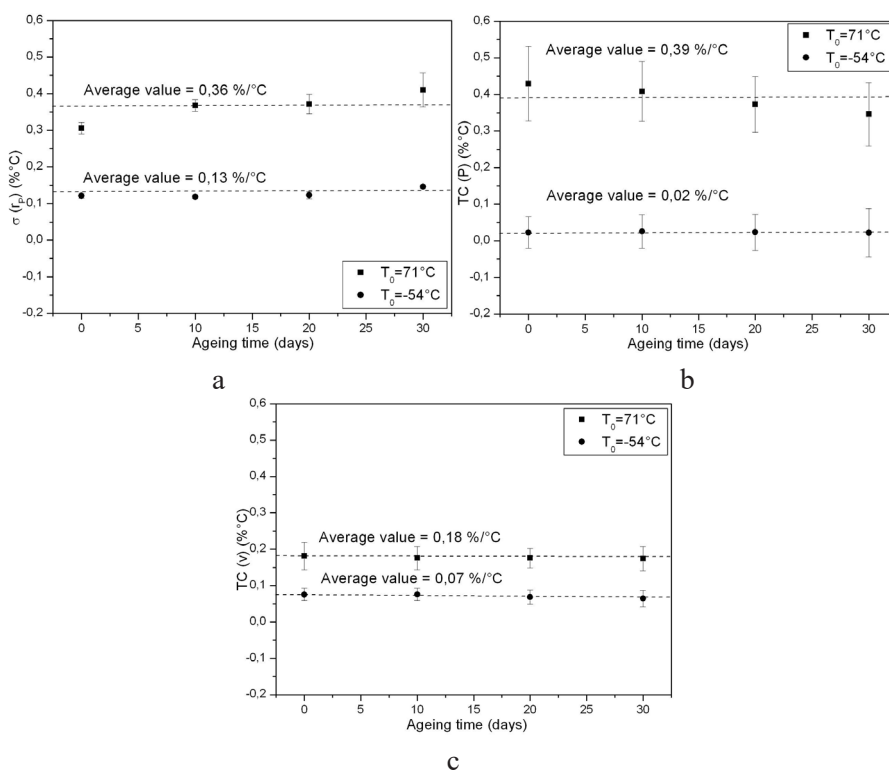


Figure 7. Influence of ageing on the temperature sensitivity (a) ($\sigma(r_p)$) and temperature coefficients (b) ($TC(P)$) and (c) ($TC(v)$) of the spherical propellant across the experimental range of temperatures. The displayed error bars are +1 Standard Deviation (SD). The dashed lines are the average values over the whole range of ageing times.

Figure 7 represents the influence of ageing on the temperature sensitivity and temperature coefficients. According to the closed vessel test results, the

ageing of the propellant resulted in an increase of $\sigma(r_p)$ for the initial propellant temperature of 71 °C and no significant variation in the temperature sensitivity coefficients towards lower initial temperatures (Figure 7a). $TC(P)$ decreased with ageing towards higher initial temperatures and no significant variation of $TC(P)$ was noticed at the initial temperature of -54 °C (Figure 7b). We observed no significant variation of $TC(v)$ as a function of ageing (Figure 7c). Despite the fact that $\sigma(r_p)$ and $TC(P)$ showed an increase and a decrease as a function of ageing for the higher initial temperature, respectively, we considered that it was a minor variation. Indeed, the values of the temperature sensitivity and temperature coefficients averaged over the whole ageing period (0 to 30 days) illustrated in Figure 7 by the horizontal dashed lines were determined with an error less than 12%.

6 Results – Flattened Propellant

6.1 Unaged propellant

As with the spherical propellant, the temperature sensitivity $\sigma(r_p)$ of the unaged flattened propellant was almost constant over the entire range of pressures (Table 5).

Table 5. Values of the temperature sensitivity $\sigma(r_p)$ of the unaged flattened propellant at pressures ranging from 50 MPa to 110 MPa (30% to 70% of the maximum pressure inside the closed vessel). Values in parenthesis are one Standard Deviation (+1SD)

Pressure [MPa]	$\sigma(r_p)$ [%/°C]	
	71 °C/21 °C	21 °C/-54 °C
50	0.239	0.120
60	0.218	0.115
70	0.181	0.117
80	0.231	0.110
90	0.276	0.104
100	0.225	0.110
110	0.233	0.128
Average	0.229 (± 0.028)	0.115 (± 0.008)

Table 6. Values of the temperature sensitivity $\sigma(r_p)$ and the temperature coefficients ($TC(P)$) and ($TC(v)$) of the unaged spherical and flattened propellants across the experimental range of temperatures 71 °C / -54 °C. The value in parenthesis is one Standard Deviation (+1SD)

Shape	Spherical propellant		Flattened propellant	
	Range of temperatures		Range of temperatures	
	71 °C/21 °C	21 °C/-54 °C	71 °C/21 °C	21 °C/-54 °C
$\sigma(r_p)$	0.305 (± 0.016)	0.121 (± 0.006)	0.229 (± 0.028)	0.115 (± 0.008)
TC (P)	0.429 (± 0.102)	0.022 (± 0.043)	0.239 (± 0.110)	0.037 (± 0.052)
TC (v)	0.177 (± 0.003)	0.075 (± 0.017)	0.090 (± 0.026)	0.051 (± 0.018)

Table 6 summarizes the values of the temperature sensitivity and temperature coefficients of the unaged spherical and flattened propellants. As with the spherical propellant, the temperature sensitivity and temperature coefficients of the flattened propellant showed larger values in the range of higher initial temperatures (71 °C/21 °C). Moreover, it was observed that the flattened propellant was less temperature sensitive than its spherical analogue towards the higher initial temperatures. Also the temperature coefficients obtained by the firing tests using the flattened propellant were smaller than the temperature coefficients of the spherical propellant in the range of higher initial temperatures. This is consistent with the data reported in [3]. For both propellants, similar temperature sensitivity coefficients and temperature coefficients were observed towards the lower initial temperatures.

6.2 Aged propellant

Figure 8 represents all temperature sensitivity coefficients and temperature coefficients of the spherical and flattened propellants, for the various ageing times. As for the spherical propellant, we consider that ageing results in minor changes of the temperature sensitivity of the burning rate and the temperature coefficients. Indeed, the values of the temperature sensitivity and temperature coefficients of the flattened propellant averaged over the whole ageing period (0 to 30 days), and illustrated in Figure 8 by the horizontal dashed lines, were determined with an error less than 13%.

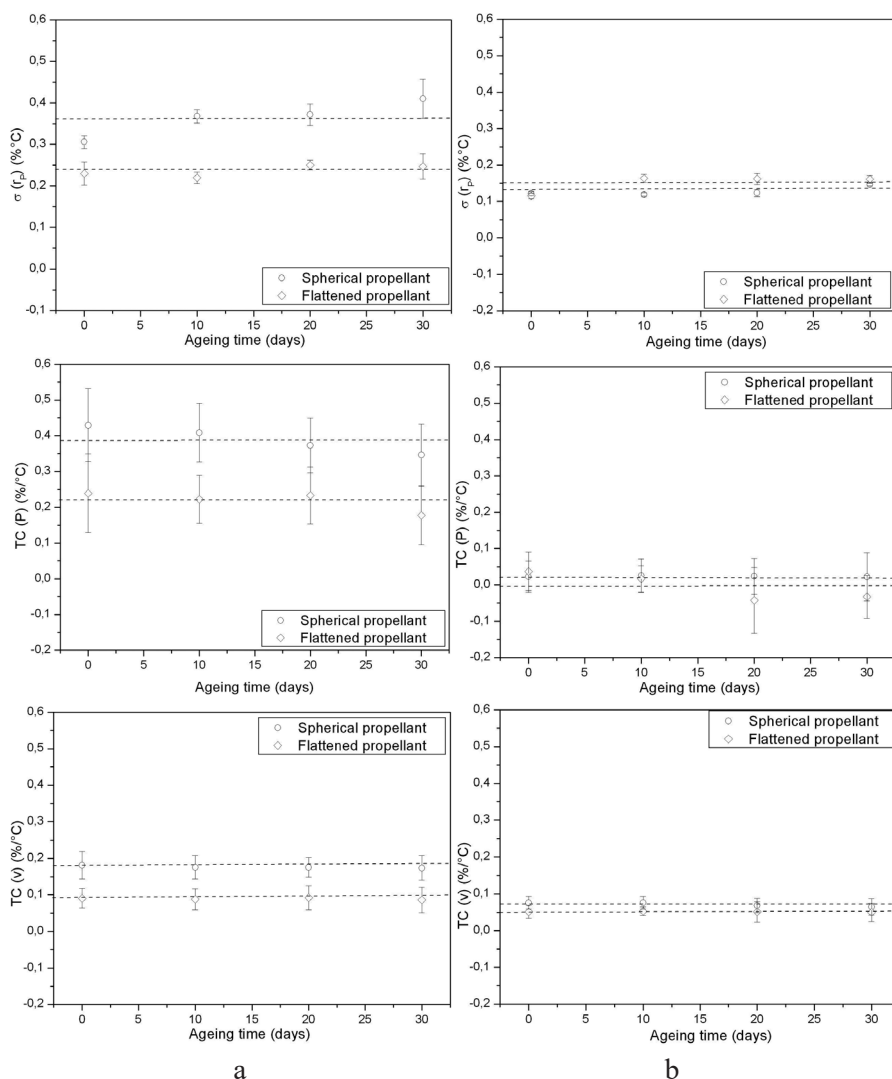


Figure 8. Temperature sensitivity ($\sigma(r_p)$) and temperature coefficients ($TC(P)$) and ($TC(v)$) of the unaged and aged spherical and flattened propellants. (a) In the range 71 °C/21 °C, and (b) in the range 21 °C/-54 °C. The displayed error bars are +1 Standard Deviation (SD). The dashed lines are the average values over the whole range of ageing times.

7 Discussion

At the lower temperatures (21 °C/−54 °C), we observed no significant variation of the maximum pressure inside the cartridge as a function of the initial temperature for spherical propellants (Figure 4). We speculate that at lower initial temperatures, the blast pressure waves produced by the ignition of the primer at the base of the propellant bed (Figure 9) accelerate the propellant grains forward to impact the projectile base resulting in grain fracture. Consequently the burning surface is increased, compensating for the small decrease in the burning rate of the propellant when the initial temperature is decreased. This assumption will be the subject of further analysis of the mechanical properties of the propellant in a future study.

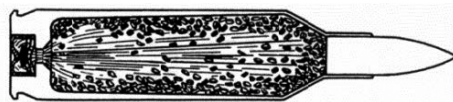


Figure 9. Illustration of the compaction of the propellant bed under the ignition conditions.

A correspondence was observed between the temperature sensitivity of the burning rate and the temperature coefficients obtained from closed vessel tests and ballistic firings, respectively. Indeed, the calculated temperature sensitivities and temperature coefficients showed that the flattened propellant was less sensitive than the spherical propellant in the range of the higher initial temperatures. For both propellants, similar temperature sensitivities and temperature coefficients were observed towards the lower initial temperatures. Additionally, it was observed that ageing results in minor changes in the temperature sensitivities and temperature coefficients for both propellants.

This correspondence results in an increased interest in using closed vessels for propellant characterisation. One must note that closed vessel tests are much less infrastructure and time demanding than ballistic firings.

This study was carried out under specific operating conditions which were defined by the type of cartridge, the loading density, the composition of the propellant charge, the primer composition and its design. It is important to note that the change of one or more of these parameters could influence the temperature coefficients [2].

8 Conclusions

Selected definitions of temperature sensitivity and temperature coefficients have been applied to investigate the relations between the temperature sensitivity and temperature coefficients using closed vessel tests (burning rate) and firing tests (maximum pressure and projectile velocity).

It has been demonstrated that the selected definition of the temperature sensitivity of the burning rate is adequate to describe the temperature sensitivity of the propellants investigated. In fact, to define the temperature sensitivity of the burning rate, it is often assumed that, in the traditional Vieille's law, $r_p = b \cdot P^n$, the pressure exponent, n , is not a function of the initial temperature; it has been shown here that this assumption is plausible for the propellants investigated.

For the two propellant types investigated a correspondence has been observed between the temperature sensitivity of the propellant burning rate as obtained from closed vessel tests and the temperature coefficients of the peak pressure in the weapon and the projectile velocity as obtained from ballistic firings. In the higher initial temperature range, the investigated spherical propellant exhibited greater temperature sensitivity and temperature coefficients than the flattened propellant. For both propellants, similar temperature sensitivity and temperature coefficients were observed towards the lower initial temperatures. We consider that ageing results in minor changes to both the temperature sensitivity of the burning rate and the temperature coefficients of both propellants.

This correspondence suggests that assessing the temperature sensitivity of the burning rate of propellants by closed vessel tests is of added value to the range of ballistic tests. One must note that closed vessel tests have the advantage that they can be carried out rapidly and relatively easily. By comparison, ballistic firing requires appropriate laboratory conditions and infrastructure, and thus results in an increased interest in employing closed vessel tests for propellant characterisation.

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