Modelling and experiments of enclosure solid-propellant fires

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Abstract. In order to simulate an accidental propellant fire, blocks of aluminized solid rocket propellant, with mass in the range of 2-11 kg, were burned in a full-scale enclosure representative of an ammunition storage room onboard naval vessel. Wall heat flux and temperature, as well as gas pressure and temperature were measured to provide information regarding fire behaviour and thermal response of the structure. Burn characteristics of the propellant block, including shape and geometry, were deduced from visible and infrared images. The role of confinement, interior wall insulation or water spray on fire consequences was also investigated. Simulation results from a global model were compared to some experimental data. Agreement and discrepancies were identified.

1. Introduction

More stable and easier to store than liquid-fuel rockets, solid-propellant rockets are still used for military and space purposes (e.g. air-to-air and air-to-ground missiles, model rockets, or boosters for satellite launchers). On board naval vessels, solid-propellant rockets are stored in ammunition rooms, which raises the problem of safety due to the risk of possible ignition when exposed to fire or during handling.

The burning of solid-rocket propellant (SRP) can generate a high-temperature (~3000K) flame [1], which in turn can propagate the fire to remote targets and/or lead to damage of the vessel structure. Estimating the thermal effects generated by the combustion of solid-propellant rockets within enclosures, under nearly atmospheric conditions, is a challenge in terms of scientific knowledge and safety assessment. In the last five decades, combustion of SRP has been widely studied (see [2-15], to name but a few). Basic phenomena (e.g. physics-chemistry, the ignition process, and additive and pressure effects on the burning rate) are generally studied on a small scale, with samples varying from a few milligrams to a few grams. Due to the hazardous nature of solid propellants and the strict rules associated with their use, only a small number of available studies are dedicated to the burning of propellant specimens of the order of one kilogram or more [8-11].

From a numerical point of view, various models have been developed to predict SRP combustion. The comprehensive review of Beckstead et al [15] summarized the main studies on the modeling and simulation of solid-propellant ignition and combustion for various propellant types over a wide range
of ambient conditions. On the other hand, despite the potential hazards of propellants, only a few studies are available regarding the thermal impact of a propellant fire on surroundings. In France, the first attempt to model SRP fires inside compartments was done by Fournier and Lallemand, using both one-zone and CFD models [16]. In [17], Giroud et al studied the behavior of a homogeneous double-base propellant fire in a shipboard compartment featuring a ceiling safety vent. Some years later, Williams et al [18] modified the computer fire model FAST, a zone model developed by the NIST (National Institute of Standards and Technology), to characterize the environment of shipboard compartments. A good agreement between data and calculations was obtained in terms of time evolutions of upper layer temperatures and floor level total heat flux. Chassagne et al [9,10] used the NIST Fire Dynamics Simulator to predict thermal issues related to ambient AP/HTPB/Al propellant fires. The comparative analysis of model and experiments revealed a good agreement of temperatures within the flame and an overestimation of the radiative heat exchanges between the flame and the environment.

The present study follows on from these works by first collecting data on the combustion of aluminized propellant blocks (here, Butalane®), with a mass in the range of 2-11 kg, in a full-scale enclosure representative of an ammunition storage room onboard naval vessel. The measurements that are reported in this study are the burn characteristics of the propellant (e.g. mass, burning rate or geometry), the wall heat flux and temperature, and the gas pressure and temperature, as well as information on the block shape and geometry from visible and infrared post-processed images. The effects of confinement, wall insulation, and water spray on fire consequences are also studied. Secondly, some of these data are used to test a global numerical model developed by DGA TN.

2. Experiments and results

2.1. Fire facility

DECIMA (a French acronym for Experimental Device for the Characterization of Active Materials) is a pyrotechnic fire test facility located on the military site of Tourris of DGA TN. It was designed to evaluate the thermal response of a steel structure, representative of an ammunition storage room onboard naval vessel, exposed to midscale propellant fires. DECIMA is composed of two adjacent rooms of 48 m³ each (i.e. 4m×4m×3m), with 6 mm thick steel walls (figure 1). Combustion products can escape from the enclosure through a 50cm×50cm vent that can be permanently open (natural vent) or equipped with an explosion vent that opens as soon as the room overpressure exceeds a pre-set value.

In the present experiments, the propellant block was placed on an elevated pedestal located on the centre of one room (figure 2) and maintained by a steel grid to prevent its displacement during the tests. Ignition was initiated using a bag of black powder placed on the top face of the block.

Figure 1. The experimental facility. Figure 2. A 11 kg propellant block prior ignition.
Schematic views of the experimental facility showing major technical components and scientific instrumentation used for fire experiments are given in figure 3.

The pedestal was placed on a thermally insulated SARTORIUS® electronic balance to measure mass loss with an accuracy of ±1 g, a response time of 0.1 s and a frequency of 1 Hz. Wall temperature were measured with twenty-nine K-type thermocouples positioned on the outside of the walls of the fire room. Four vertical trees of five jacketed thermocouples spaced 50 cm apart, were placed at 1 m from the walls to measure gas temperature. Total and radiative heat flux were recorded from two CAPTEC® gauges placed on the centre of the west and back walls. A CP114 KIMO sensor was used to measure differential pressure in the range of [-500; +500] mbar. Mole fractions of O₂, CO and CO₂ were measured by two TESTO 350 gas analysers, one located in the vicinity of the explosion vent at a height of 2.27 m, the other near the front wall at mid-height (hereafter called GA1). One monochrome CCD camera, with a resolution of 1600px × 1200px and a frequency of 10 Hz, and one infrared camera, with a spectral range of 7.4-14 mm, were located outside the enclosure to obtain side views of the burning sample. A filter was added to the CCD camera, that attenuates the visible radiation from the flame, and a ZnSe window was mounted flush with the west wall to allow for the transmission of IR light from the sample. A digital image post-processing methodology developed by Pizzo et al [19] was used to track the location of the regressing burning surface. This also required a specific adjustment of the camera shutters. Another difficulty with propellant fire tests was that operators had to remain confined in a bunker during the test, which ruled out any further modification of camera pre-sets.

2.2. Experimental test matrix

More than 30 experiments were conducted in DECIMA, varying the geometry of propellant blocks (cylindrical for blocks A and B, and parallelepipedal for block C), the insulation conditions (no insulation, external or internal wall insulation), the opening conditions (explosion vent or natural opening), and the water spraying conditions. The propellant used was Butalane®, a 68/12/20 AP/HTPB/Al (68% ammonium perchlorate, 12% hydroxyl-terminated polybutadiene and 20% aluminium) composite propellant, with an average density of 1710.3 ± 6 kg/m³, produced by the HERAKLES Group for military and space applications [9,10]. A selection of five relevant and representative experiments, that will be analysed below, is presented in table 1.
Table 1. Test matrix.

| Test case | Propellant block | Insulation | Opening | Water spray system |
|-----------|------------------|------------|---------|-------------------|
| #1        | A                | Ø202.7×H200.1 | 11011   | Explosion vent    | -      |
| #2        | B                | Ø89.6×H200.1 | 2157    | Explosion vent    | -      |
| #3        | C                | 1.99.8×H190.8×H90.5 | 1408   | Explosion vent    | -      |
| #4        | A                | Ø202.5×H200.4 | 11038   | Interior wall     | Permanent |
| #5        | A                | Ø202.6×H200.2 | 11029   | -                 | Permanent From 40 to 80 s |

The aluminized USeaPROTECT® mineral wool by ISOVER, with a thickness of 60 mm and a density of 36 kg/m³, was used for test case #4 to provide a A-60 standard insulation (A-60 means a 60 minutes fire protection) as recommended for ammunition storage rooms. For test case #5, a spray system with four 12 mm diameter finned nozzles, developed by Focus Industrie, was activated 40 s after ignition for 40 s. The nozzles were positioned at 1 m from the walls and 0.1 m from the ceiling. At a pressure of 8 bars, this type of nozzle gives a hollow cone, with an average Sauter diameter $d_{32}$ of about 310 μm and a nominal water flow rate of 16000 L/h.

2.3. Experimental results

2.3.1. Test case #1: a baseline test case  Examination of the videos by infrared and visible cameras, from which the images in figure 4 were extracted, shows that: i) the upper surface of the block is totally inflamed after approximately 4 s; ii) after approximately 38 s of fire, the flame front passes under the block which then burns over its entire surface and begins to levitate; and iii) flaming combustion stops after 91 s. Images from the CCD camera were post-processed to provide information on the burn characteristics of the sample. It was found that the burning sample exhibits a truncated-cone-shaped structure, with a burning surface regression rate of about 1.3 mm/s and a flame spread rate four times larger.

As shown in figure 5, the opening of the explosion vent occurs approximately 7 s after ignition. The overpressure in the room at this time (or dynamic burst pressure $p_{burst}$) is 91 mbar, which is in accordance with the manufacturer’s data.

If we compare the changes over time in the masses of block A obtained during test case #1 and in the open air (e.g. in [20]) (figure 5), we can see that they are very similar. The differences observed are due to differences in block ignition, but also, in a confined environment, to the pressure waves which have impacted the support of the electronic balance during the test. After 38 s, when the block begins to levitate, the entire surface of the block is in combustion, which leads to a rapid increase in the burning rate, with a maximum value of 277 g/s. This value can be compared to that obtained during the open air burning of block A, i.e. 260 g/s, showing a weak influence of confinement on combustion.

The gas temperatures measured at the four corners of the source room at different heights change rapidly over time, reaching in the upper part, a few seconds after the burning rate is maximum, a relatively high level, up to 640°C (figure 6 and figure 7). Thermal stratification of smoke is observed throughout the test, except in the back-west corner (figure 7), especially at a height of 2 m, when the combustion rate decreases. This is due to fresh air inlets in the lower part of the vent, as confirmed by the observations.

The oxygen level measured by GA1 (figure 8) decreases to 11.3% due to two combined effects: the oxygen is forced out the enclosure by the combustion products, but it can also be reduced by the oxidation of these products (e.g. post-combustion CO-O₂ [9,17]). It then takes time to return to its atmospheric level, the exit of combustion products limiting the entry of fresh air through the opening. The CO content in the combustion products is relatively low as a result of two competitive effects, namely the gain linked to the propellant combustion and the oxidative reaction of degraded hydrocarbons (post-combustion CₓHᵧ=O₂), and the loss linked to its oxidation [9].

The total heat flux received by the side walls (figure 9) are mainly convective, with a small contribution of radiation (maximum 3.7 kW/m²) due to the low emissivity of the propellant flame and
smoke density. They can reach high values, close to 30 kW/m². The maximum wall temperature is obtained at the center of the ceiling, directly above the burning block, with 139°C (figure 10). On the side walls, this maximum is observed on the back wall, with 91°C (figure 11), due to the preferential path of the combustion products towards the opening on this wall.

![Figure 4](image)

**Figure 4.** Test case #1: infrared (left) and CCD (right) camera images of burning block A at t = 10, 20, 30, and 40 s.
Figure 5. Test case #1: mass of block A and differential pressure vs. time. Also plotted the time evolution of the mass of block A burning in the open air.

Figure 6. Test case #1: gas temperatures in the front-west corner of the fire room vs. time.

Figure 7. Test case #1: gas temperatures in the back-west corner of the fire room vs. time.

Figure 8. Test case #1: mole fractions of CO and O₂ measured by GA1 vs. time.

Figure 9. Test case #1: wall heat flux vs. time.
2.3.2. Effects of propellant block type on fire consequences The influence of the propellant block geometry, and thus of its mass and surface, is studied by comparing test cases #1 to #3. Table 2 summarizes the main results obtained from these experiments.

For the three test cases, the achieved values of the dynamic burst pressure were in the range given by the manufacturer (i.e. 100 ± 25 mbar). The increase of room pressure depends on the rate at which the surface of the block is covered by the flame and levitation occurs, which explains why the explosion vent opens earlier for block A than blocks B and C. As observed for block A, pressure waves generated by the propellant combustion and the vent burst during test cases #2 and #3 have impacted the support of the electronic scale, leading to large fluctuations in the mass-history curves (figure 12). However, ignoring these fluctuations, the time evolution of the mass of each block is very similar to that obtained for open air experiments. Therefore, confinement has a weak effect on propellant combustion, which was an expected result since burning rate depends on pressure as \( p^n \), with \( n \sim 1 \) [3], and pressure increase did not exceed 110 mbar.

Whatever the block type, smoke stratification is observed. The combustion of blocks B and C generates a lower quantity of combustion products than bloc A which results in lower gas and wall temperatures, heat flux, and CO production (table 2). Unlike test case #1 where a significant air vitiation is observed in the enclosure, oxygen mole fraction deviates little from its atmospheric value for test cases #2 and #3, with minimum values of 19.5 and 19.9%.

Table 2. Test results in terms of full ignition delay \( t_{up} \) (time between ignition and the time at which the upper surface of the block is totally inflated), burst pressure and delay \( p_{burst} \) and \( t_{burst} \), block levitation delay \( t_{lev} \), flaming combustion duration \( t_{fc} \), maximum values of gas temperature \( T_{max} \), wall temperature \( T_{w_{max}} \), wall heat flux \( \Phi_{w_{max}} \), and CO mole fraction \( X_{CO_{max}} \), and minimum value of O\(_2\) mole fraction \( X_{O2_{min}} \).

| Test case | \( t_{up} \) (s) | \( p_{burst} \) (mbar/s) | \( t_{burst} \) (s) | \( t_{lev} \) (s) | \( t_{fc} \) (s) | \( T_{max} \) (°C) | \( T_{w_{max}} \) (°C) | \( \Phi_{w_{max}} \) (kW/m\(^2\)) | \( X_{CO_{max}} \) (ppm) | \( X_{O2_{min}} \) (%) |
|-----------|-----------------|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| #1        | 4               | 91/7                    | 38              | 91              | 637             | 139             | 29              | 72              | 11.3            |                 |
| #2        | 4               | 107/15                  | 41              | 61              | 245             | 60              | 8               | 10              | 19.5            |                 |
| #3        | 2               | 97/9                    | 13              | 39              | 190             | 53              | 6               | 6               | 19.9            |                 |
| #4        | 11              | -/-                     | 37              | 91              | 1049            | 126             | 40770           | 0               |                 |
| #5        | 11              | -/-                     | 37              | 91              | 1049            | 126             | 40770           | 0               |                 |

* from the two heat flux gauges.

* from the two analysers.
Figure 12. Mass of the block and differential pressure vs. time for test cases #2 (left) and #3 (right).

Also plotted in each diagram the time evolution of the mass of the block burning in the open air.

2.3.3. Effects of internal wall insulation on fire consequences

For test case #4, the enclosure was insulated from the inside using an aluminized mineral wool. All the data were used, except for some wall temperature measurements, due to the antenna effect generated by the aluminized coating. Remember that for this test the opening was permanently open.

Regarding the behavior of the insulation material, except for the lower part of the side walls, the adhesive joint covers and the aluminized coating were destroyed, and the rock wool layer was severely degraded. The expansion of the combustion products produces only a slight overpressure in the room, around 1.6 mbar, these products being evacuated naturally by the event. If we compare the temporal changes in the mass of block A measured during test cases #1 and #4 (figure 13), we can observe that the room insulation, despite the atmosphere it had produced, had little effect on the propellant combustion.

The insulation reduces heat loss to the outside and the radiant heat flux arriving on the walls is largely reflected by the aluminized coating, then absorbed by the optically dense gas phase inside the room. Gas temperature then rises to very high levels, up to 1050°C in the upper part of the room, while that obtained for test case #1 barely reaches 600°C (figure 14).

Mainly due to the significant release of combustion products, the oxygen content in the room drops rapidly to zero (figure 15). Moreover, the CO produced by the propellant combustion is only slightly oxidized. This leads to high CO concentrations, which can locally exceed 4%.

The very high gas temperature levels generate significant heat fluxes. The total flux can reach 126.1 kW/m² on the west wall (figure 16), with a radiative contribution of 20.5 kW/m² (not shown). The radiative part appears relatively low. This may be due to the low emissivity of the propellant flame, but also to a high optical density of smoke.

Although the antenna effect generated by the aluminized layer of the insulation disturbed wall temperature measurements, the analysis of the usable measurements reveals a very small rise in these temperatures, around 10°C (not shown).
2.3.4. Effects of water spray on fire consequences During test case #5, mass measurement was disturbed by spraying, which makes it unusable. Spray activation, at \( t = 40 \) s, generates a slight room under-pressure, which allows fresh air to intermittently enter the room through the natural vent. The drops that constitute the spray have a mean Sauter diameter of about 310 \( \mu \)m, which gives them a good inertia/specific surface ratio. The heat absorbed by the vapor and the liquid leads to the cooling of the gas phase (figure 17) in the decay phase of fire. After only 27 s of spraying, the maximum temperature of the gas in the room drops below 100°C.

Due to mixing, sprinkling breaks smoke stratification, with a quasi-homogenization of temperature in the room. Gas cooling and flow mixing tend to limit the reactions in the gas phase and, consequently, the depletion of oxygen (figure 18). The CO produced accumulates in the room, leading to a concentration in the room almost seven times higher than that measured during test case #1. Unlike test case #1, the depression of the room, even intermittent, favors the air intake and the return of oxygen to its atmospheric level. The latter returns to 20% after 360 s.

The total flux received by the west wall (figure 19) is greatly reduced compared to test case #1, up to almost 15 kW/m², due to a decrease in both convective (the gas phase is cooler and turbulence mitigated by the spray) and radiative (radiation is attenuated by the gaseous medium charged with water vapor and droplets) contributions. This phenomenon, combined with the cooling induced by the deposition of water droplets on the walls, has the effect of causing saturation, or even a decrease, of the wall temperatures compared to those of test case #1 (e.g. north wall in figure 20).
3. Model results and comparison with experiments

3.1. The MEGALO® model
The global numerical model MEGALO® has been developed by DGA TN to evaluate the atmosphere induced by an ammunition fire in a multicompartiment storage enclosure, in terms of gas pressure and temperature, and wall temperature. The evacuation of the combustion products from the enclosure can be done through an exhaust chimney (or plenum) or an explosion vent. The model is based on the mass and energy conservation equations that are solved in each room and plenum using a fourth order Runge-Kutta method. A specific treatment of explosion venting is required to handle the outflow boundary conditions while satisfying mass and energy conservation.

3.2. Comparison with experiments
The model was applied to test cases #1 to #3 involving three different types of propellant blocks. The combustion rate of the propellant block was calculated from an analytical model [20] based on geometrical considerations and the intrinsic regression rate of the solid propellant determined experimentally, namely 1.3±0.1 mm/s.

As mentioned previously, the measurement of the mass was disturbed by the pressure waves impacting the electronic scale support when the explosion vent opened, especially for blocks B and C.
(figure 21). The analytical model cannot reproduce these findings, but correctly reproduce the observed average mass-time curves for the three propellant blocks considered. The combustion rate (or mass loss rate), which is an input data of the model, was obtained from the time derivation of the predicted mass loss for each type of block.

![Mass-time curves for Blocks A, B, and C](image1)

**Figure 21.** Mass histories of blocks A, B and C, obtained from the analytical model and test cases #1 to #3.

The comparison between model results and measurements is presented in figure 22 and figure 23, in terms of gas and wall temperatures, and differential pressure. The model captures the pressure profile with a good agreement. The temperature peak is also fairly well reproduced by the model. However, after the propellant combustion is completed, gas temperature is underestimated, which suggests a faster cooling of the gas phase than that observed in the experiments. MEGALO® is based on a simplified reaction mechanism which cannot describe in detail the complex chemical composition of the propellant combustion products, and thus their thermal inertia and radiative contribution. This gas temperature deficit leads to lower heat transfers between the gas and the walls than experiments (figure 23).

![Temperature and pressure profiles for Blocks A and B](image2)
Figure 22. Time evolution of gas temperature (left column) and differential pressure (right column) obtained from the model and experiments for propellant blocks A, B and C.

Figure 23. Time evolution of ceiling and side wall temperatures, obtained from the MEGALO model and experiments for propellant blocks A, B and C.
4. Conclusions
Blocks of aluminized solid rocket propellant, with a mass in the range of 2-11 kg, have been burned in a full-scale enclosure representative of an ammunition storage room. The effects of block geometry, internal insulation of wall enclosure and water spray on fire behaviour and thermal response of the structure have been studied. Some data collected have been used to validate a global combustion model. A good agreement has been observed on the time evolution of pressure and gas temperature levels. However, the model fails to correctly reproduce the cooling phase of the fire due to an overly simplified reaction model. A better description of the chemical composition of the propellant combustion products is a matter for further study.

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