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Evaluating the Effect of Grain Geometry and the Particle Size of Ammonium Perchlorate on the Combustion of Base Bleed Propellants in Static Firing Tests

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Abstract. A traditional way to develop extended range munition (ERM) is through the insertion of the combustion products generated by the burning propellant in the rear part of the projectile. This is the so-called base bleed system (BB). This work aims to evaluate the performance of BB propellants as a function of grain geometries and the mean particle sizes of the ammonium perchlorate (AP) when tested in static firing. The static tests are performed on a lab-scale bench, designed and built in-house, where a cylindrical combustion chamber, with the same dimensions as the 114.3 mm projectile, is fixed to a sliding table. Thrust and internal chamber pressure are measured. The mass flow is corrected to account for projectile rotation and base pressure along the trajectory, using correlations from the literature. Results indicate that when the propellant regression rate is too high, it generates high mass flow rates in the early stages of the propellant combustion and rashly consumes the propellant grain. This is the case for the BB propellant with a smaller mean particle size of AP. On the other hand, a very low regression rate (with a coarser mean particle size of AP) leads to a delayed plateau of the mass flow regimes. Those effects on a real firing performance of Base Bleed propellant are discussed. Regarding propellant grain geometry, it affected mainly the ignition delay. Smaller internal diameter is related to a faster ignition process. Finally, the evaluations performed in this work are very useful for further estimation of aerodynamic parameters and projectile flight simulation in real operational conditions.

Keywords: Base Bleed; Propellant; Extended range munition; Static firing tests; Ammonium perchlorate

1. INTRODUCTION

A munition projectile has a limited range in great part due to the aerodynamic base drag, where the resistance is caused by the vacuum formed in the rear part of the projectile. One way to partially overcome this drag is through the mass flow of combustion products generated by the burning of a propellant in the rear part of a projectile, a system called Base Bleed (BB) (Belaidouni et al, 2016; Bournot et al, 2006; Lemos et al, 2017; Xue & Yu, 2016; Zhang et al, 2017; Börngen & Hahn, 1988). The Figure 1 shows a scheme of a projectile with a BB system assembled in the rear part.

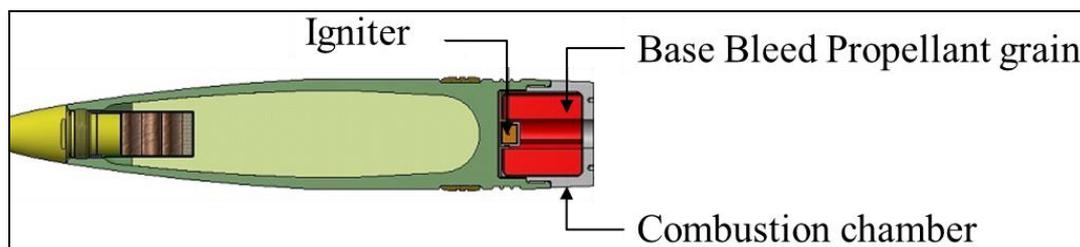


Figure 1. Example of an ammunition with a Base Bleed system assembled in the rear part. Consisting of a combustion chamber with a propellant grain and a pyrotechnic igniter inside.

The Base Bleed system consists basically of a combustion chamber with an inserted propellant which is ignited by an igniter after the firing of the artillery shell.

Base bleed propellants have several differences and some similarities to rocket engines. They can be similar in chemical formulation, being produced for example from a polyurethane using the Hydroxy-terminated Liquid Polybutadiene (HTPB) as the polyol, filled with particles of an oxidizing salt, typically ammonium perchlorate (AP), and aluminum particles (Bournot et al, 2006; Lemos et al, 2017; Zhang et al, 2017). On the other hand, during operation, Base Bleed propellants should not generate additional thrust (at least not much), but to burn at low-pressure regimes, unlike the rocket engines. It is already known that the regression rate of propellants, means the rate which propellant is burnt, strongly depends on the AP amount and its particle size distribution, as well as the pressure in the combustion chamber. The burning of propellants with several AP particle sizes and amounts in high-pressure regimes is already well described in the literature, for example in the work of Thomas et al (2018). However, propellants for Base Bleed usually burn slower, mainly due to lower chamber pressures and its operation under sub atmospheric conditions (Kayser et al, 1991). A relevant aspect, which significantly increases the propellant's regression rate due to the erosive burning, is the projectile's spin, which must be considered when modeling the Base Bleed gas mass flow for the cases of extended-range projectiles (Kayser et al, 1988).

There are no definitive conjugations of models available to allow the estimation of the propellant performance in terms of ballistics without the need of real firing tests, meaning only by simple lab-scale bench tests under static conditions. Dragoslav (1988) and Fetherolf et al (1988) performed lab-scale static tests to evaluate ignition of pyrotechnic-based BB formulation. Some authors reported propellant testing under high spin rate, to simulate BB conditions after firing in a proving ground (Kayser et al, 1991; Kayser et al, 1988; Fetherolf et al, 1988). However, there are not a definitive solution for this matter. On the other hand, testing the BB systems in a real proving ground demands high costs with logistics and ammunition manufacture.

To deal with this challenge, a joint group of researchers from the Brazilian Navy, the State University of Rio de Janeiro, and the company EMGEPRON developed since 2019 several models and experimental setups to test several BB systems consisting of several propellant formulations and configuration. Pinheiro et al (2020) proposed an experimental setup to investigate the performance of Base Bleed propellants in static bench. Lucena et al (2020) investigated the supersonic flow around an artillery projectile to relate the influence of the BB on the drag coefficient using CFD. More recently, Lemos et al (2022) presented some results of range prediction of selected BB formulations.

The current work is a continuation of this ongoing effort. Here, it is presented an approach to evaluate the effect of ammonium perchlorate particle size and the propellant grain geometry in the mass flow regime of BB propellant tested in static tests conditions, and how the mass flow rate tested under static conditions can be extrapolated to consider operational environment, where the effects of spin rate of projectile and pressure from altitude variation change the propellant regression rate. Therefore, to predict their performance in real firing conditions, a correction for the spin rate and the pressure variation along the trajectory is necessary and is evaluated in this work.

2. EXPERIMENTAL

2.1 Propellant manufacture

To manufacture the composite solid propellants used in Base Bleed systems, the following raw materials were used: oxidizer salt ammonium perchlorate (AP) sieved at several particle sizes, from AEQ Aliança Eletroquímica Ltda; aluminum powder available at IPqM; polyol hydroxyl-terminated polybutadiene (HTPB), from former Petroflex company, donated by AVIBRAS Industria Aeroespacial S/A (Brazil); Isophorone diisocyanate (IPDI), from Merck. Propellants are mixed for 6 hours in a planetary vertical kneader (DAY mixer) with three sigma rods, at 60°C and high vacuum.

Table 1 describes the main data of the propellant grains manufactured for this study. Two different internal geometries are adopted as molds to vary the regression regime, the first called here as “flower” (Figure 2 - left) and the

other called “circular” geometry (Figure 2 - right). The formulations also varied in terms of mean particle size AP distribution.

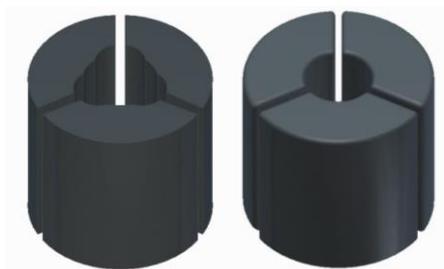


Figure 2. Propellant grain geometries. The flower (left) and the circular (right) geometries.

After casting the dough in the mold, the propellant cured for 7 days in an oven cabinet at 60°C. At the end, the extracted propellant with adequate mechanical properties is ready for static test.

Table 1. The main data of the propellants manufactured for this study.

Sample code* **	Mean particle size (µm)	Internal grain geometry	Internal diameter (mm)	Internal surface area (mm ²)
fAP-C	145	circular	31	8073
fAP-F	145	flower	33-44	10027
mAP-F	175			
cAP-F	290			

* f refers to “fine”; m refers do “medium”; c refers to “coarse”. Regarding AP mean particle size.

** C is circular; F refers to a flower. Regarding internal grain geometry.

2.2 Experimental and modelling of static tests

The static tests methodology and modelling followed the work already published in the last ENCIT meeting (Pinheiro et al, 2020). Tests were performed in a lab-scale bench, designed, and built in-house, where a cylindrical combustion chamber, with the same dimensions of the 4.5” projectile, is fixed to a sliding table. In the Figures 3 and 4 a 3D representation and a picture of a static test are shown. The table is fixed by pillow blocks to a linear guide rail that allows only horizontal sliding, in the axial direction of the combustion chamber. A 200N capacity load cell is attached between a sliding table and a fixed table, to accurately measure the thrust originated by the propellant burning. The pressure in the combustion chamber is also measured by means of an absolute pressure transducer, with a pressure range from 0 to 2.1 bar (absolute). The thrust is measured by using a load cell calibrated before each static firing test. The data is acquired by a NI-9219 A/D module, from NI®, connected to the USB port of a computer running a special data logger software using LabVIEW®. The computer stores the force and pressure measurements, and the measurement synchronization is started by the ignition signal, which fires a squib to initiate a pyrotechnic igniter and then the propellant grain of the Base Bleed.

In the Figure 3 a 3D representation of the static test bench is demonstrated. The calibration of the force transducer is performed by the hanged cable with pre-defined weights which are placed gradually in the metal plate to pull the combustion chamber against the transducer in a 50 g step. In the Figure 4, a picture of a static test is shown to demonstrate how the combustion products are expelled from the test chamber.

The BB is basically a device in which a propellant burn to generate hot gases through a throat, similarly to a rocket propellant but without nozzle. Figure 5 depicts the main elements of a static test system, where the BB device is fixed to a support S equipped with a load cell to measure the thrust F, generated by the BB during its combustion. Although the thrust measured is relatively low, it can provide valuable information for estimating BB device operational variables, like the mass flow, throat speed and chamber pressure, allowing the BB performance to be evaluated and improved. Besides, the static test system the additional pressure transducer to measure the chamber pressure.

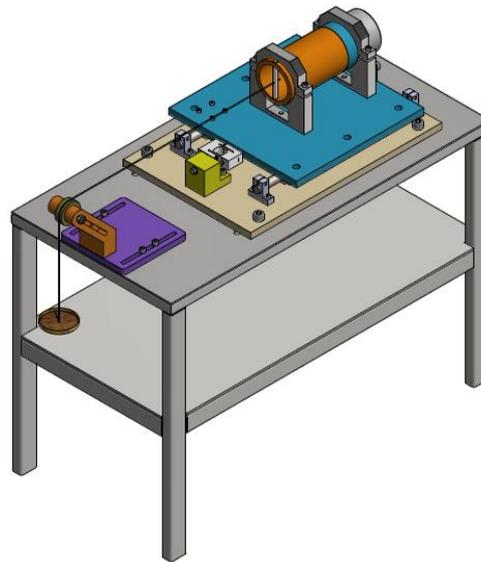


Figure 3. 3D representation of the static test bench developed to test BB propellants. The table is fixed by pillow blocks to a linear guide rail that allows only horizontal sliding against a force transducer.



Figure 4. Example of a static combustion test of a Base Bleed propellant in the test bench developed for this work.

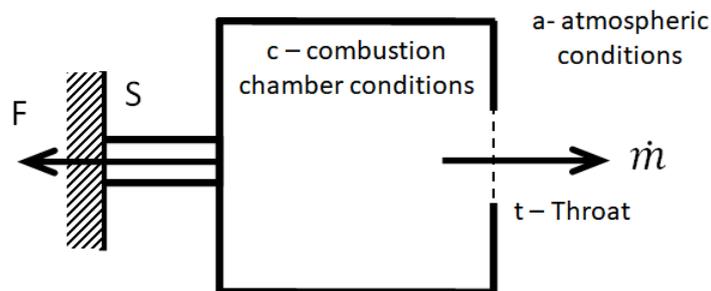


Figure 5. The Static Test System. Showing the Base Bleed device fixed to the stand S.

The mathematical modelling of the static test is already described elsewhere (Pinheiro et al, 2020). In summary, the mass flow rate (\dot{m}) generated by the combustion of the Base Bleed propellant can be calculated as function of thrust or chamber pressure measurements, according to equation 1 and 2, respectively.

$$F = \dot{m}V_t \quad (1)$$

$$\dot{m} = \frac{2kP_c A_t}{k-1} \left(\frac{P_c}{P_t}\right)^{1/k} \left[\left(\frac{P_c}{P_t}\right)^{(k-1)/k} - 1 \right] \quad (2)$$

Where F is the axial thrust, V_t is the gas exhaust velocity through the throat, A_t is the section area of the throat, P_c is the chamber pressure, P_t is the throat pressure, P_a is the ambient pressure nearby the throat and k is the isentropic constant. It is considered that the hot gases generated inside the combustion chamber flow through the throat as an isentropic flow (Zucrow et al, 1976).

The base bleed mass flow rate values obtained from the static tests, hereon referred as \dot{m}_{BB} , do not consider the pressure and spin rate variations along the flight trajectory, typical for any gun projectile. Therefore, a correction is necessary. For this purpose, it is considered that the mass burn rate is a function of the burned mass m_B , hence $\dot{m}_{BB} = \dot{m}_{BB}(m_B)$, and that, for the same burned mass, the instantaneous grain burning area in the static test is the same as in the real firing test. Therefore \dot{m}_{BB} , and consequently $m_B(t)$, are correspondingly corrected using actual flight trajectory data. Mass flow rates from the static tests are corrected by using Saint Robert's Law (Sutton & Biblarz, 2016). As well as by the spin rate influence (Kayser et al, 1988). As a result, the Equation 3 is established for the corrected mass flow rate.

$$\dot{m}_{BBcorrected}(m_B) = \dot{m}_{BB}(m_B) k_r(\Omega) \left(\frac{P_{tb}}{P_{tt}}\right)^n \quad (3)$$

Where k_r is the spin correction factor; $\dot{m}_{BB}(m_B)$ is the mass flow rate obtained in the static tests for a certain burned mass m_B ; P_{tb} is the pressure in the rear of the BB unit during the flight; P_{tt} is the ambient pressure at the test bench; and $n = 0.6655$, from Kayser et al (1988). Thus, the corrected mass flow rate is obtained and can be employed subsequently in an aerodynamic mathematical model to estimate the drag coefficient variations which will be produced by a specific base bleed unit tested in the lab bench, under real firing conditions.

3. RESULTS

The normalized mass flow rate calculated from the static test of the four selected samples are plotted in Figure 6, showing the full-time scale of the test. The absolute numerical results are hindered due to confidentiality issues. Mass flow rate is not yet corrected according to spin and atmospheric pressure. It is important to evaluate the first moments after ignitions of the propellant because this is a time interval where the projectile is at its maximum speed and the drag is very high due to the low altitude (projectile fires at an initial muzzle velocity of around 880 m.s^{-1}).

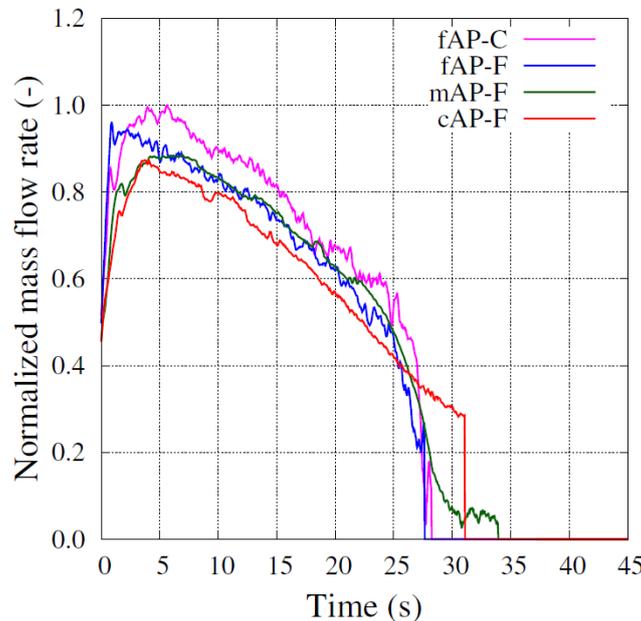


Figure 6. Normalized mass flow rate as a function of time in the static tests, without corrections regarding pressure and rotation during real firing conditions, showed at full time scale.

The comparison regarding internal geometry between fAP-C and fAP-F suggests that the second (flower geometry) generates more mass flow in the earlier stages of the test (between 1 to 2 s after ignition), probably due to its higher internal surface area (10027 mm^2). However, after approximately 2.5 s there is an inversion, and the propellant with circular geometry reaches its maximum mass flow rate and it keeps the mass flow rate regime higher until the end of the test. Both formulations have their burn end nearly at the same time.

As for the ignition time, when one looks to the mass flow soon after time zero, both propellants seem to ignite similarly. A possible explanation is that smaller internal diameter of the circular geometry (31 mm) imparts closer

contact with the exhaust gases and temperature of the igniter with the propellant surface, and this may decrease the ignition delay of the propellant and compensates its smaller internal area. Jaramaz & Injac (1988) in their work with Base Bleed propellant, found that a smaller propellant grain internal diameter enhances projectile range because the ignition delay is small. They also showed that a slight delay in grain ignition can provide almost 1,000m decrease in range, for a 155mm round. Thus, it is important for a base bleed to have a fast ignition, to generate mass flow especially during the initial part of the trajectory, when the projectile is at its higher speeds. When the burn front advance further after 2 (two) seconds, the burning of the circular geometry imparts higher mass flow rate, probably due to the burn surface change with burning time.

Regarding the AP particle size, results indicate that the propellant with a higher AP mean particle size (cAP) has a slower ignition. However, as the burn front advances further, an inversion takes place, and the cAP reaches its maximum mass flow rate earlier than mAP propellant. The finer the AP mean particle size, the faster the propellant burns, and thus the total burn time is smaller. The total grain burn time of cAP is the longest, about 32 s. The mass flow rate fluctuations of the mAP after 30 seconds are perturbation of the test and may not be considered for real operational application.

It is important to highlight that the experimental setup proposed in this work has a different instrumentation and configuration objective, which is not properly adequate to evaluate the ignition process, where a more detailed analysis is possible by using high-speed camera and a higher sampling frequency of the thrust and pressure measurements. Future experiments are planned with more precise analysis of ignition process.

The mass flow rates obtained in static tests need to be corrected to consider both the rotation speed of the projectile after real firing and the actual BB exit pressure along the trajectory. By applying such corrections, the results are plotted in Figure 5a and b.

There seems to be two concurring phenomena affecting the regression rate of the propellant grain. One is the pressure drop with altitude, that decreases the regression rate of propellants, whereas the spin rate from the rotation speed of the projectile that accelerates the regression rate (Kayser, 1988). In earlier stages of the trajectory, where the spin rate is the highest (starting around 1950 rad/s), and the pressure is closer to atmosphere conditions, the propellant grain burns much faster in real firing than in static conditions. However, along the trajectory the pressure decreases (Kayser et al, 1990) and its effect on the burning rate becomes more relevant. In addition, the spin rate decreases until around 1500 rad/s in the highest altitude. Therefore, the propellant regression rate decreases, and the mass flow rate curve elongates to longer times. As a result, the corrections applied to the curves suggests that a higher burn time of the propellant is reached in a real firing test compared to the test under static conditions, for the case studied in this work.

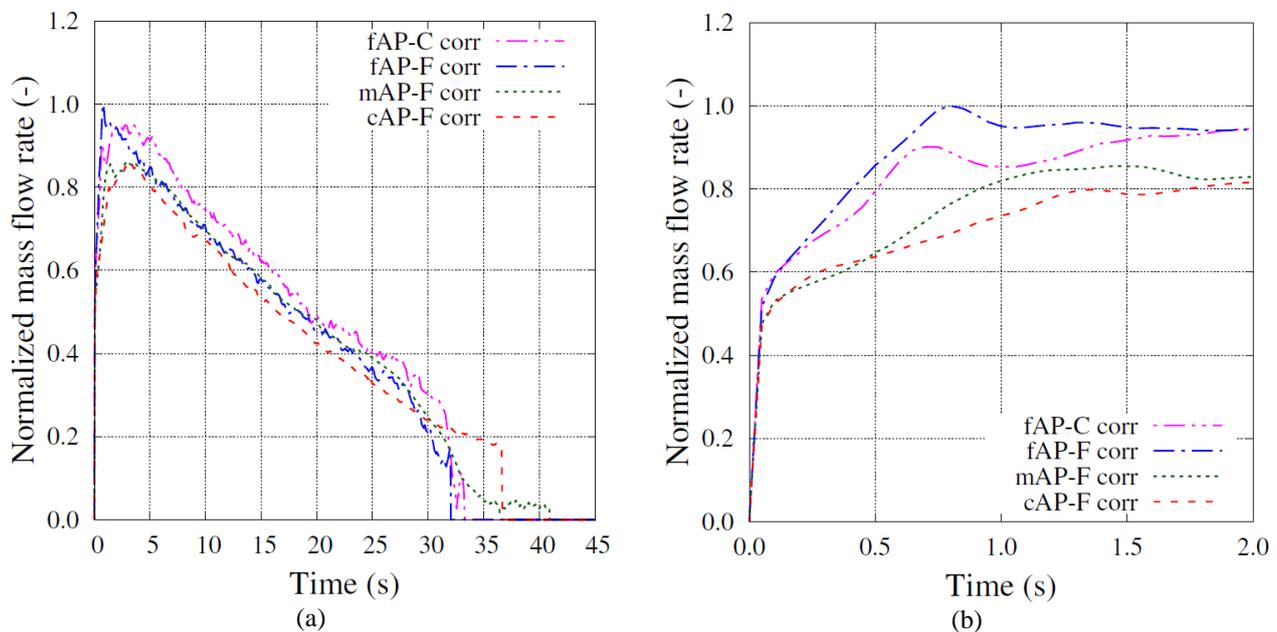


Figure 5. Mass flow rate as a function of time in the static tests, WITH the corrections regarding pressure and rotation during real firing conditions, (a) at full time scale and (b) in the first 2 (two) seconds after ignition.

Regarding the predicted results in real firing conditions, one can expect that a higher mass flow generation especially in earlier stages of the projectile is beneficial for higher drag reduction, and thus allows the projectile reaching longer ranges. However, the final trajectory is a compromise of both the burn rate and the total burn time of the propellant. If a propellant burns too fast, it consumes the BB very early; whereas a very slow burn produces less mass flow rate and hence less drag reduction. This was demonstrated by Abou-Elela et al (2013), where it was

investigated several BB propellant formulations giving several different regression rates. They demonstrated that the maximum range in real firing tests is reached in an intermediary value.

Therefore, further tests are being developed and are necessary to understand more deeply the effects of ignition time and regression rate in the performance of Base Bleed propellant in real firing tests.

4. CONCLUSIONS

The present work presented an evaluation of the performance of Base Bleed (BB) propellants for 114.3 mm caliber guns under static firing conditions, as a function of propellant grain geometries and mean particle sizes of the ammonium perchlorate in the formulation. The evaluation was performed through static bench tests, especially developed to test BB propellants.

It was found that the internal geometry and surface area affected the mass flow rate soon after the ignition stage. A higher internal surface area imparts higher mass flow rate in the earlier stages of the static firing tests, whereas a smaller internal diameter allows closer contact with hot gases from the igniter, thus providing a faster ignition.

The propellant filled with the ammonium perchlorate with higher mean particle size presented the slower ignition and regression rate, and a higher burn time.

By correcting the mass flow rate to take into account spin rate and pressure variation in real firing conditions, it was verified that the maximum mass flow rate is shifted to earlier times. Spin rate has a major effect on the regression rate especially in the seconds after ignition.

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