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SIMULATION AND STATIC TESTS OF BASE BLEED GAS GENERATORS

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Abstract. *This paper aims to present some algorithms and models developed to provide a good prediction of the performance of extended range munitions, thus reducing the need of several real shooting tests. One of the key factors of base bleed devices is the mass flow of the gas generator, that can be estimated by using data acquired from simple lab scale test bench. The results of some static tests, along with the respective modeling and calculated operational conditions will be presented. The developed algorithms and models showed good results, in agreement with the expected values and the available literature, that will assist in the simulation and modeling of extended range munition.*

Keywords: *base bleed, static test, propulsion, rocket, computer simulation, extended range munitions*

1. INTRODUCTION

A flying object such as a munition projectile has a limited range in part due to aerodynamic drag, where the main resistance is caused by the low pressure formed in the rear part of the projectile, causing the so called "base drag". One way to increase rear pressure is through the insertion of combustion products generated by the burning of a propellant, a system called Base Bleed (BB) (Belaidouni *et al.*, 2016; Lemos *et al.*, 2017; Xue and Yu, 2016). A munition with a BB system is normally called as an "extended range" (ER) munition. The design of a propellant to be used in such system is not simple and there are few manufacturers around the globe (Borngen and Hahn, 1988; Gunners *et al.*, 1988). Hence, there are no models or commercially available software to be used to predict a specific propellant formulation which will deliver the desired performance - the only way is through a real test in a shooting range, which demands a costly logistics and great risks. Therefore, it is remarkably interesting to develop lab scale tests and models to predict the performance of extended range projectiles, without the need of several real shooting tests. This article is part of a research to develop a network of models and algorithms that might allow a good prediction of the performance of extended range munitions by using simple lab scale test bench. In this context, this work presents some results of static tests and the results of the modeling already developed, that allow the prediction of mass flow rate and thermodynamic properties of base blade generators in actual conditions.

2. THEORY OF A BASE BLEED GAS GENERATOR

The gas generating device of a base bleed has some similarities with a rocket motor. But, differently from a rocket motor, its not intended to generate thrust to the projectile. Instead, it must generate enough gases to decrease the aerodynamic drag of the projectile fired by a cannon, allowing to increase its range.

The performance of a BB gas generating device (GGD) can be evaluated through static tests, where the device is fixed to a support S capable of measuring the thrust F generated by the device, as shown in Fig. 1. Although the thrust generated is relatively low, the analysis of the thrust values can provide valuable information to improve the performance of GGD and help to obtain other information, as will be show.
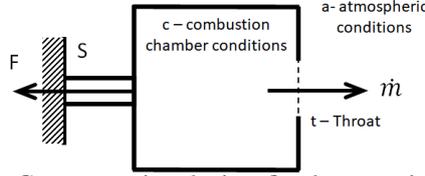

Figure 1: Gas generating device, fixed to a static test base

The axial thrust of a rocket motor (Sutton and Biblarz, 2016) is described by Eq. (1).

$$F = \dot{m}V_t + A_t(P_t - P_a) \tag{1}$$

Comparing with a rocket motor, and as the Fig. 1 shows, the GGD is a simple device, being composed by a combustion chamber, where a solid propellant is burned, and an exit throat. For the case of interest, the throat is basically a hole with square borders. Therefore, the pressures $P_t = P_a$, and the thrust is given by Eq. (2).

$$F = \dot{m}V_t \tag{2}$$

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_t is throat pressure and P_a in the ambient pressure nearby the throat. Being a closed vessel with a throat, the flow of gas through the throat of the GGD can be considered as isentropic, and the mass flow (Zucrow $et\ al.$, 1976) be calculated using the Eq. (3).

$$\dot{m} = \rho_t A_t V_t = \frac{P_c A_t}{\sqrt{kRT_c}}\sqrt{\frac{2k^2}{k-1}\left(\frac{P_t}{P_c}\right)^{2/k}\left[1 - \left(\frac{P_t}{P_c}\right)^{(k-1)/k}\right]} \tag{3}$$

From Eqs. (2) and (3), comes Eq. (4).

$$F = \rho_t A_t V_t^2 = \frac{2kP_c A_t}{k-1}\left[\left(\frac{P_c}{P_t}\right)^{(k-1)/k} - 1\right]\left(\frac{P_c}{P_t}\right)^{1/k} \tag{4}$$

3. SIMULATION OF A BASE BLEED GAS GENERATOR FROM STATIC TESTS

With the need to calculate the operating conditions of the gas generator, like mass flow, chamber pressure, chamber temperature, throat temperature, molar weight, k and so on. Its necessary to develop a procedure to simulate the GGD.

Having the static test data, the thrust versus time curve, its possible to calculate the main operational conditions of the GGD. First of all, its necessary to calculate the chamber pressure P_c, knowing the corresponding thrust F and P_t. Finding the root of the Eq. (5), assuming k as basically constant.

$$\phi(P_c, P_t, F) = \frac{2kP_c A_t}{k-1}\left[\left(\frac{P_c}{P_t}\right)^{(k-1)/k} - 1\right]\left(\frac{P_c}{P_t}\right)^{1/k} - F \tag{5}$$

The Eq. (5), comes from Eq. (4), aiming to calculate corresponding operational points (P_c, P_t, F), where $\phi(P_c, P_t, F) = 0$ for each set. During the static test, the ambient pressure is constant and know, and being $P_t = P_a$. The Eq. (5) was developed only to find the value of P_c that corresponds to the measured values of P_t and F.

Knowing the chamber pressure, P_c, and the chemical composition of the propellant, the chamber temperature, T_c, the molar weight MW and k can be calculated using the program CEA. The program CEA (Chemical Analysis with Applications) was developed by (Sanford and McBride, 1996) and is widely used to determine the composition of combustion products and to calculate the adiabatic temperature, molar weight, isentropic coefficient, enthalpy, Gibbs energy and other properties. CEA has been used in rocket propulsion and similar application since decades (Sutton and Biblarz, 2016).

From some know composition (Dali and Jaramaz, 2019) of base bleed propellant, AP=76 %, HTPB=22 %, Al=2 %, in weight. And a series of P_c values, one can run CEA for each condition, to get T_c, MW, k and calculate $\dot{m}$ using Eq. (3), T_t using Eq. (6), and the Mach number, at the throat section M_t, can be calculated using using Eq. (7), according (Zucrow $et\ al.$, 1976) .

$$T_t = T_c\left(\frac{P_t}{P_c}\right)^{(k-1)/k} \tag{6}$$

$$M_t = \sqrt{\frac{2}{k-1}\left[\left(\frac{P_c}{P_t}\right)^{(k-1)/k} - 1\right]} \tag{7}$$

4. STATIC TEST EVALUATION

A static test bench was specifically built to measure the thrust of BB devices using a load cell as the sole sensor. However, other variables of interest needed to be estimated. The main variable of interest is the mass flow, that was used to estimate the aerodynamic drag, munition trajectory and the extended range.

The thrust data, measured during a static test, and the chemical composition of the propellant grain are used as input to the methodology explained in Section 3.

A Matlab® program, using the equations and the methodology shown before, was built to calculate chamber pressures and temperature, mass flow, among others variables. The program interfaces with the CEA library.

The time series of thrust values, measured during the static test of three samples of propellant grain are shown in Fig. 2.

(a) Thrust vs Time - Sample 1   (b) Thrust vs Time - Sample 2   (c) Thrust vs Time - Sample 3
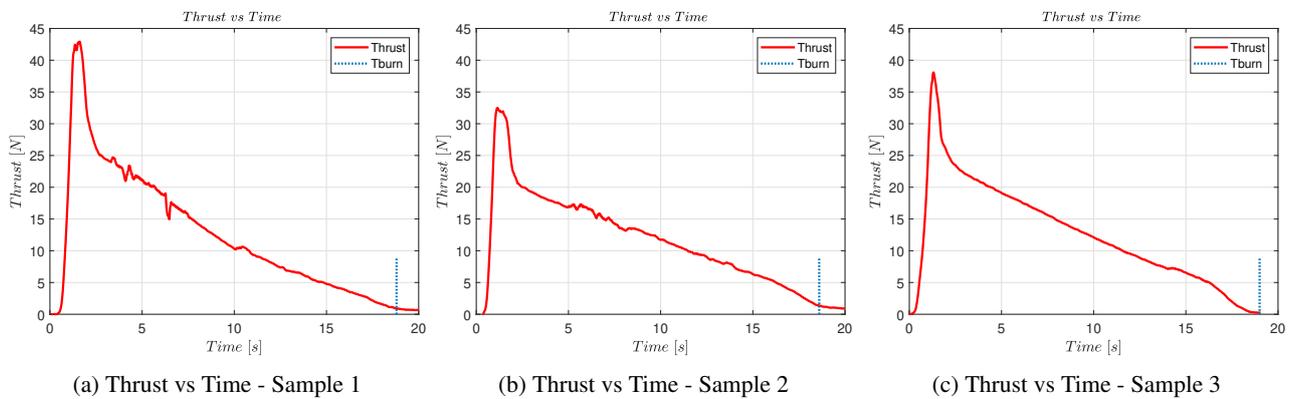
Figure 2: Thrust vs Time, static test of 3 samples

The three tested samples had the same composition of grain, the propellant is mainly composed by ammonium perchlorate, HTPB and aluminum. The burning time was almost the same for the three samples, as seen in Fig. 2, of almost 19 seconds. And the sample 1 presented the greater thrust peak.

Using the Eq. (5), the chamber pressure during the test of each sample was calculated. The chamber temperature T_c is calculated using the CEA program, and the throat temperature is calculated using Eq. (6). From the thrust values shown in Fig. 2, the calculated chamber pressure and temperatures values, P_c, T_c and T_t, are shown respectively in Fig. 3 and Fig. 4.

(a) P_c vs Time - Sample 1   (b) P_c vs Time - Sample 2   (c) P_c vs Time - Sample 3
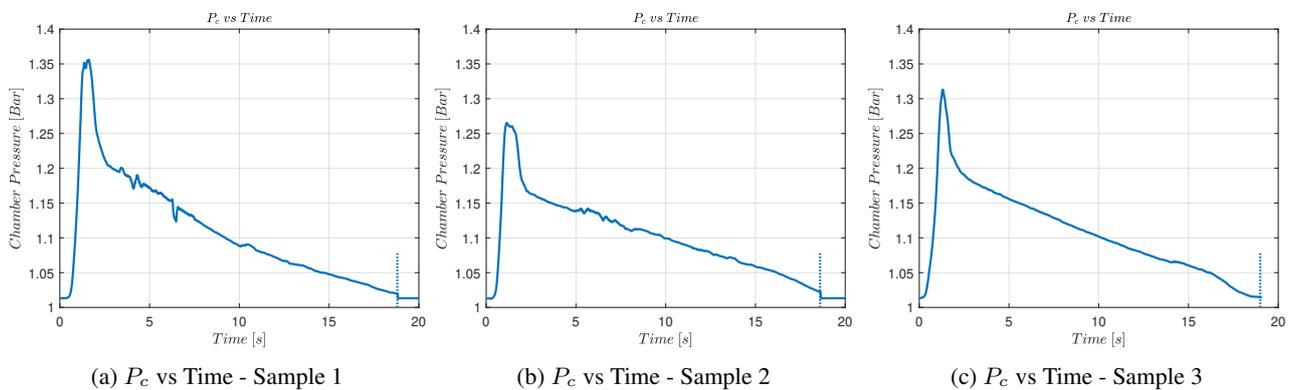
Figure 3: Chamber Pressure - P_c vs Time, calculated for each sample

In Fig. 4, the chamber temperature T_c is almost constant and the throat temperature T_t experiences a small drop, due the energy balance, with an increase of the kinematic energy and the throat speed V_t, due the increase of the chamber pressure P_c. Using the previous values of $T_c(t)$, $P_c(t)$ and the Eq. (3), the mass flow $\dot{m}(t)$, for each sample tested are also calculated and shown in Fig. 5.
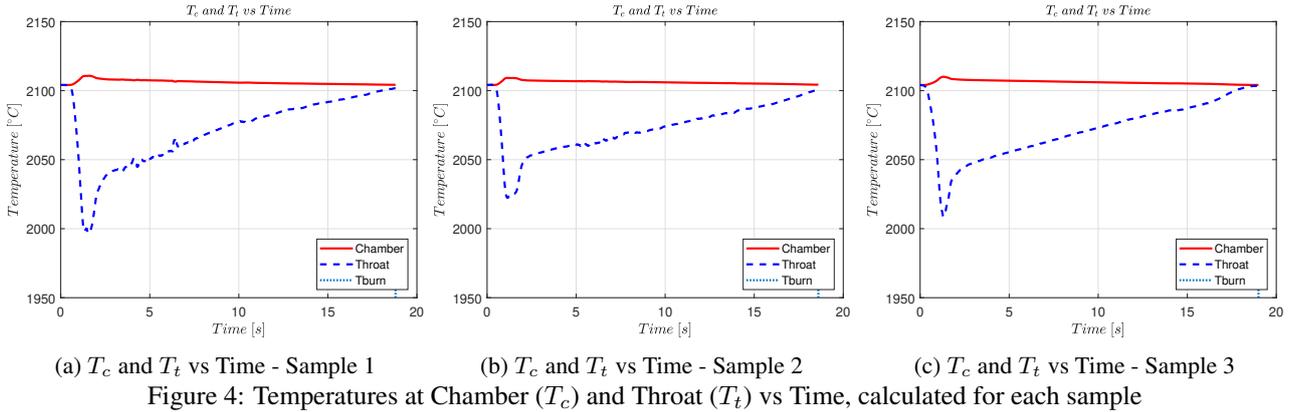
(a) T_c and T_t vs Time - Sample 1   (b) T_c and T_t vs Time - Sample 2   (c) T_c and T_t vs Time - Sample 3

Figure 4: Temperatures at Chamber (T_c) and Throat (T_t) vs Time, calculated for each sample

(a) $\dot{m}(t)$ vs Time - Sample 1   (b) $\dot{m}(t)$ vs Time - Sample 2   (c) $\dot{m}(t)$ vs Time - Sample 3
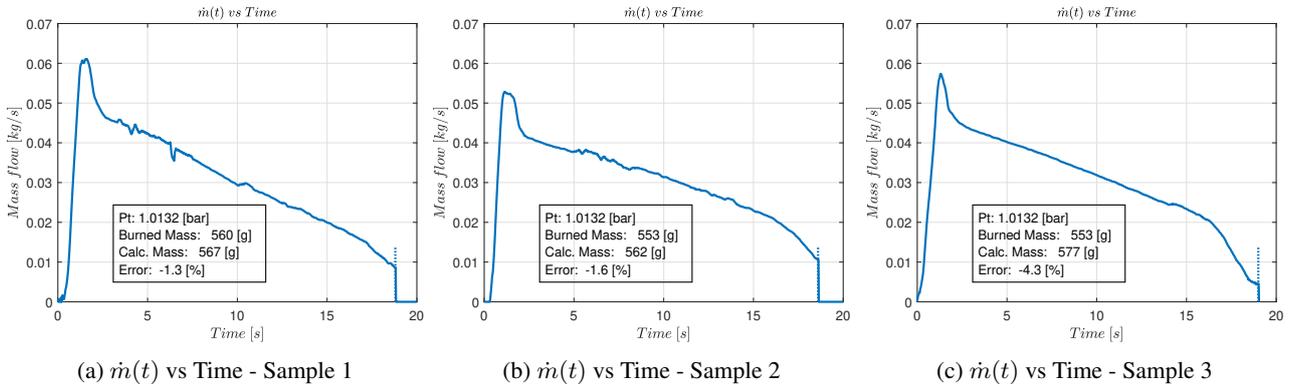
Figure 5: Mass flow rate - $\dot{m}(t)$ vs Time, calculated for each sample

The calculated values of $\dot{m}(t)$, corresponding to each sample tested, are show in Fig. 5. On each graph, are show the throat pressure P_t, the mass of the propellant grain before the test, the calculated mass after the test and the error between these values. By integrating of the $\dot{m}(t)$ curve, the corresponding calculated mass m_{calc} was obtained, according the Eq. (8).

$$m_{calc} = \int_0^{T_{burn}} \dot{m}(t)\,dt \tag{8}$$

The measured and calculated mass, after the static test of the three samples are shown in the Tab. 1.

Table 1: Measured and calculated mass m_{calc}

Sample	Measured Mass (g)	Calculated Mass (g)	Error (%)
1	560	567	-1.3
2	553	562	-1.6
3	553	577	-4.3

According the Tab. 1, for each sample tested, the measured and calculated mass are close, showing the good fit of the modeling for the mass flow, with an average error of -2.4 %. Furthermore, the calculated chamber pressure values, P_c, show in Fig. 3, are also compatible with results found in static tests (Kayser *et al.*, 1988) and as expected in some similar works (Frem, 2018; Youssef *et al.*, 2019).

5. CONCLUSIONS

This article presented some algorithms and models, which were evaluated by means of test values of thrust from some static tests and knowing the mass of the propellant grain. Three samples were tested, and the measured and calculated mass were close, with an average error of -2.4 %. Showing the good fit for the mass flow modeling, the main variable of interest in static tests, to estimate the aerodynamic drag, munition trajectory and the range, that will assist in the simulation and modeling of the extended range ammunition.

The developed algorithms and models also showed good results, in agreement with the expected values and the available literature.

The new methodology presented in this work is unusual, as it used only one load cell to collect the thrust input information necessary for modeling other operational information, such as chamber pressure and temperature. And checking the model against the propellant grain mass. In addition, the chamber temperature is very high, requiring special thermocouples. Other sensors will be installed on the static test base, for comparison with the measured values of temperature and pressure of the chamber.

6. ACKNOWLEDGEMENTS

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