Analysis of SRM propellant using the BATES platform

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Abstract

A new propellant containing a composition of 68% Ammonium Perchlorate, 18% Aluminium, and 14% HTPB was test fired within a BATES platform. A total of 27 test firings were carried out spread across 3 different nozzle throat diameters and corresponding characteristic velocities, c^*_{exp}, were calculated from acquiring the pressure of the combustion chamber during each firing. The corresponding c^*_{ideal} for every c^*_{exp} was determined with the aid of the NASA CEA software and the efficiency, η^* calculated.

Nomenclature

Acronyms

BATES **BA**llistic **T**est and **E**valuation **S**ystem

BC Bayern Chemie

SRM Solid Rocket Motor

1 Experimental Setup

A new type of propellant has been developed and required testing to determine the model parameters and performance. The propellant being examined is composed of 68% Ammonium Perchlorate, 18% Aluminium, and 14% HTPB with percentages relating to mass ratios.

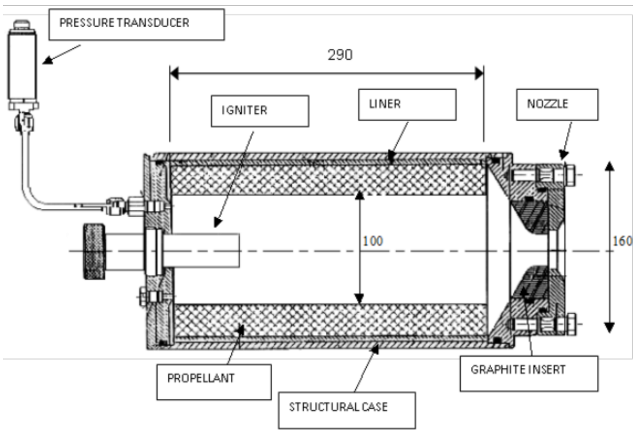

Figure 1: *A schematic of the BATES motor used in the data gathering.*

9 batches of propellant were test fired on each of the 3 available nozzle throat diameters leading to 27 individual data sets. The propellant was tested on the BATES platform, of which the dimensions are shown in Figure 1, and the three different nozzles sizes lead to three differing pressure variants, as shown in Table 1.

Table 1: *The pressure variants and the corresponding nozzle throat diameters used in the test firings.*

Pressure Variant	**Low**	**Mid**	**High**
⌀ [mm]	28.80	25.25	21.81

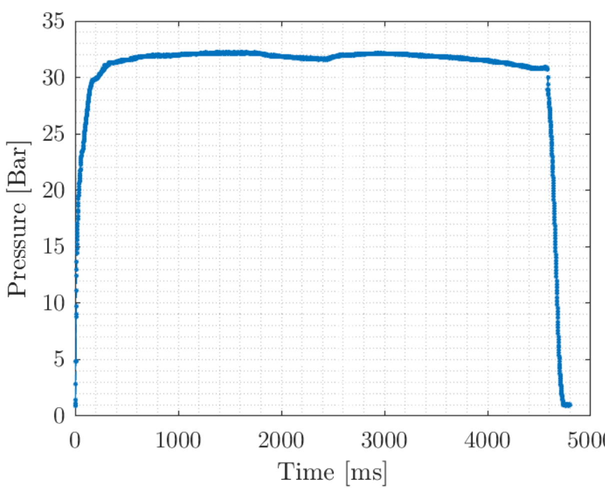

Figure 2: *An example of the given data. This is a test firing using the low pressure variant nozzle.*

A pressure transducer within the BATES platform recorded the combustion chamber pressure, at a sampling rate of 1kHz, during each firing resulting in a pressure-time trace. An example of the acquired data is shown in Figure 2.

2 Experimental c^* and r_b

An algorithm based on the BC method was developed in Matlab in order to calculate and determine the burning rate and effective pressure for an individual pressure-time curve. A pressure of 5% P_{max} was utilised as the reference to define the *action* and *burning* time of the firing.

The burning rate, r_b of the propellant can be calculated using the web thickness, w_t, and the burning time, t_b, with

$$r_b = \frac{w_t}{t_b} \tag{1}$$

The w_t for this propellant, as is seen in Figure 1, was $30mm$.

The effective pressure, P_{eff}, of a pressure-time curve was determined by numerically integrating between the times when the pressure was above the reference pressure and diving by the difference between these times.

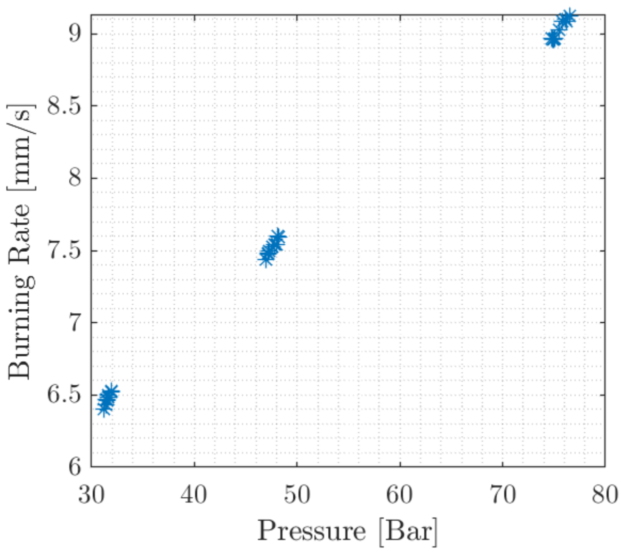

Figure 3: *Resulting analysis of the internal ballistics of the burning rate as a function of the combustion chamber operational pressure.*

The algorithm was then used to calculate P_{eff} and r_b for each batch of propellant. The results are shown in Figure 3. The three different clusters of data correspond to the three different pressure variants of experiment used in the data acquisition. The function *Uncertainty*, provided by the Politecnico di Milano, was employed to take in the computed results and calculate the coefficient values for the Vielle's law with their corresponding errors. The Vielle's law coefficients were calculated as $a = 1.7269 \pm 0.01844$ and $n = 0.3821 \pm 0.0027$.

Each batch of propellant test fired also had the corresponding c^*_{exp} calculated via

$$c^*_{exp} = \frac{\int_{t_c}^{t_b} P_c(t)dtA_t}{m_{tot}} \tag{2}$$

where A_t is the nozzle throat diameter, m_{tot} is the total mass of propellant, and P_c is the combustion chamber pressure obtained from the pressure-time curves. Analysing the all available data results in $c^*_{exp} = 1391.2 \pm 10.8$ m/s for the propellant.

3 Ideal c^*

The ideal c^* value was computed with the aid of the NASA CEA software. This software takes into account the chemical composition of the propellant and calculates the chemical and thermodynamic properties of a given burn.

The model was set to assume a frozen flow.

The nozzle ratios used within the CEA code match the different nozzle variants used in the BATES platform and the initial pressure corresponded to the aforementioned P_{eff}. The chemical composition input also matched that of the propellant and the CEA thermodynamics database was employed for the values of Aluminium component, Al(cr), and Ammonium Perchlorate, NH_4ClO_4(I). However, HTPB was manually input to have a chemical composition of $C_{7.075}H_{10.65}O_{0.223}N_{0.063}$ and a standard enthalpy of formation of -58kJ/mol.

The thermodynamic output values of the CEA were used to calculate the ratio of specific, γ, with the Mayer relation and the c^*_{ideal} with

$$c^*_{ideal} = \frac{1}{\Gamma(\gamma)} \sqrt{\frac{R}{M_{mol}} T_c} \tag{3}$$

and the definition of the Vandenkerckhove function being

$$\Gamma(\gamma) = \sqrt{\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{4}$$

Applying these equations to the collated results from the CEA software leads to a c^* value of 1554.9 ± 4.6 m/s.

4 Efficiency, η^*

Finally, the efficiency of the propellant was deduced using

$$\eta^* = \frac{c^*_{exp}}{c^*_{ideal}} \tag{5}$$

with every efficiency corresponding to an individual test firing plotted in Figure 4. Once again, the three different groupings correspond to the different nozzle types used in each test firing.

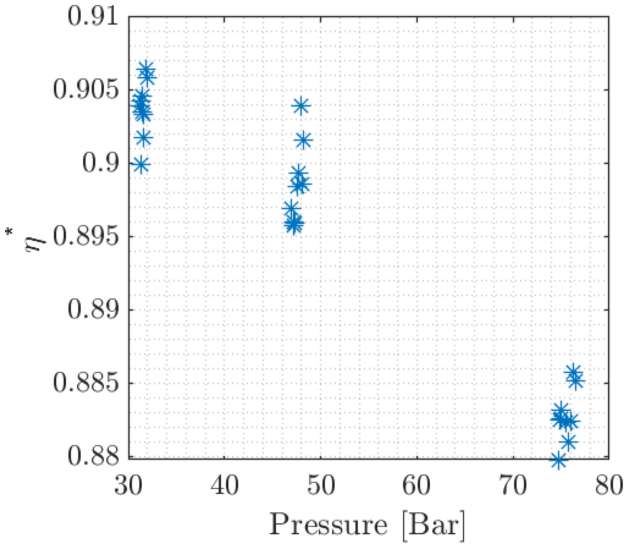

Figure 4: *Calculated values of the efficiency as a function of combustion chamber operational pressure.*

There is a general negative trend in η^* as pressure increases. This may arise as with increased pressure the velocity of the propellant within the combustion chamber increases therefore, the propellant has less time to completely burn whilst within the combustion chamber. However, due to the spread of the points within each cloud of points more data over more pressure values is required to determine the full relationship between the pressure and the efficiency.

Furthermore, this could also arise from the CEA code as the model assumes a frozen flow. Further refinement of the ideal calculation could be made by following a model which resembles the BATES motor may provide a better insight to the effect combustion chamber pressure has on the efficiency.