The determination of atmospheric pressure linear burning rates of solid propellants formulations.

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1 Introduction

Propellants are a mixture of energetic and inert substances designed such that a certain burning velocity is attained. The substances used as ingredients are selected to optimize the processability, burning behaviour and sensitivity of the formulation. Following the mixing of ingredients, a composition is extruded through a set of cylindrical dies in order to shape the product to a desired geometry. The extruded strands are then cut in a rotary cutting machine to a specific length. The geometry given to the formulation is of great importance to its combustion behaviour as it controls the available surface area. It is the combination of both the surface area and the burning velocity which defines the gas generation potential of a specific propellant sample.

Models describing propellant combustion idealize the process by assuming that all surfaces are ignited simultaneously and burn with the same velocity. This velocity, which is in a direction perpendicular to the propellant surface at a given point, is known as the linear burning rate of the propellant formulation. Due to the sensitivity of chemical reactions to the environment in which they take place, the linear burning rate of a given sample will depend on the pressure and temperature around the sample. As most propellant applications are designed to operate at pressures much larger than the atmospheric value, very few published linear burning rates results are available at low pressures. In this study, the measurement of the atmospheric pressure linear burning rate of a nitrocellulose based formulation has been performed. A short review of previous publications in linear burning rate measurements is first presented. The empirical results are then shown followed by a short discussion on their analysis.

2 Previous studies

There are two main ways by which linear burning rates have traditionally been obtained:

- Direct measurement in a strand burner.
- Calculation using closed vessel firing data.

The former technique consists in measuring the passage time of the flame front on a propellant strand ignited at one end. The sides of the strand are sometimes inhibited in order to confine the combustion

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on only one axis. Several methods have been used to measure the flame front passage time at various points on the strand: embedding thermocouples [1] or electrical wires at specific locations, filming the combustion with a known distance marker. A recent publication has proposed using infrared thermography to detect the combustion front [2]. It is important to note that the strand is usually contained in a sealed vessel which is pressurized to a desired measurement pressure prior to ignition. The advantage of this method is that it enables a direct measurement of the burning rate. Given that it is not practical to pressurize a vessel to values observed in larger pressure applications (up to 700 MPa), the strand burner is applied to cases with limited pressures.

As stated in its description, the second method yields the burning rate from a calculation and is thus indirect. The granular propellant sample is burned in a closed vessel and the generated pressure is measured using a piezoelectric transducer. From the knowledge of the geometry and thermodynamic properties of the sample, the pressure-time relationship is transformed to a gas generation rate and a linear burning rate [3]. Note that the thermodynamic properties of the combustion gases are computed using codes such as Cheetah [4] from the measured chemical composition of the formulation. Calculation routines which apply this method have been designed to aid designers [5] and the methodology has been standardized by NATO [6]. The disadvantage of this method compared the former one is that the calculation rests on the assumption of the simultaneous ignition and burning of all surfaces [3], which is known to not hold in the majority of cases. It must be noted that this methods is however used for all high pressure applications as there it is easier to apply in these cases.

Little data has been published on near atmospheric pressure burning rates since applications usually make use of the pressure dependance of the combustion. Schoyer and Korting have studied subatmospheric pressure burning rates for composite propellants [7]. Their experimental setup was based on a combination of both methods discussed above. The sample burned linearly (on one axis only) and the presure rise was measured. The setup enabled to control the combustion area while providing a more precise distance measurement then standard strand burner techniques [7]. In the case of the present study, such a method would probably prove not to be the best choice in terms of costs, precision and ease of using. The standard stand burner methods would thus most likely be a logical choice here.

3 Measurements

Experiments have been made to determine the atmospheric pressure linear burning rates of a single base propellant formulation. As discussed previously, the strand burner technique was applied to cylindrical and rectangular samples. A summary of the protocol used to obtain these measurements is shown in the following list:

1. Samples manufacturing
    a. Mixing of the single base formulation ingredients (98% nitrocellulose and 2% inert).
    b. Extrusion through cylindrical and rectangular dies.
    c. Manual cutting of the strands
    d. Drying to obtain a residual solvent level below 1.0%

2. Measurements
    a. Positioning of the sample vertically with a support at the base
    b. Positioning of the distance reference parallel to the sample
    c. Ignition at the top with a propane flame
    d. Visual recording of the combustion (Sony Cybershot camera at 30 frames per second)
    e. Measurement of the distances and times using frame by frame still images and an imaging software.

Figure 1 shows two frames of recorded combustion tests made on the single base sample. It must be noted that the initial tests were performed without inhibiting the outer surface of the samples in order to observe the effect of surface flame propagation on the results. Visual recordings have shown that the flame propagation is faster on edges then on the flat center of the strand. The combustion surface thus goes from a circular area to a steady state conical shape with all angles around 60°. This steady state shape is obtained after approximately 4.5 to 5.0 seconds and is shown on Figure 1-a. Prior to attaining its steady state, the combustion surface is that of a truncated cone. Velocities computed from the measured distances and times are summarized in the diagrams of Figure 2.

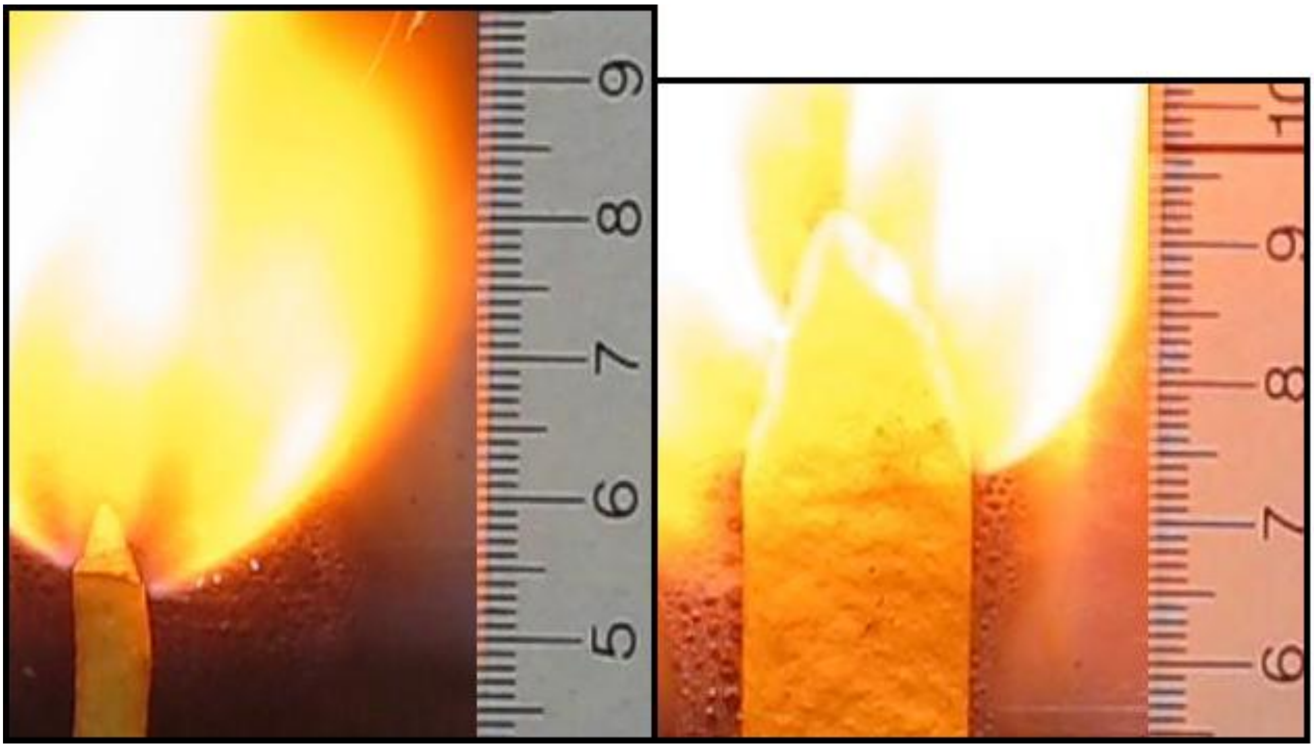

Figure 1: Sample recording stills of single base strand burning tests. Figure 1-a (left) shows the combustion of a cylindrical strand. Figure 1-b (right) shows the combustion of a rectangular strand.

4 Discussion

The velocity differences shown in Figure 2-a have been described as “edge effects” by Drysdale [8]. These effects have been studied for cases involving the combustion of polymers [9]. It is interesting to note that the 60° angle was also consistently observed by Creeden and Sibulkin in a study involving the combustion of various PMMA configurations (in that case, a value of 30° was reported since the samples were inhibited on one side) [10]. In that same study, the burning rate component normal to the edge was given to be [10]

$$V_N = V_u \sin \varphi$$

where V_N, V_u and φ are the burning rate normal to the edge, the burning rate in the vertical direction and the edge half-angle respectively [10]. Considering the average rate of 1.5 mm/s and a half-angle of 30° obtained in the present case, a value of 0.75 mm/s is calculated for V_N.

Similar tests have been done with the same batch of sample to verify the effect of inhibiting the outer surface. The propellant strands were immersed in water for 15 seconds prior to being placed on the combustion setup and ignited. The method proved to be less effective for taking measurements as the samples tended to extinguish after a few seconds of normal combustion. Some measurements were however taken and an average burning rate situated between 0.60 and 0.80 mm/s was obtained (rates between 0.37 and 1.14 mm/s were measured with the largest concentration of data points around 0.60 mm/s). Although the experiments with the inhibited samples did not yield results with the same quality as those from the pure propellant strands, it is observed that the predicted burning rate of 0.75 mm/s seems to be in the good region.

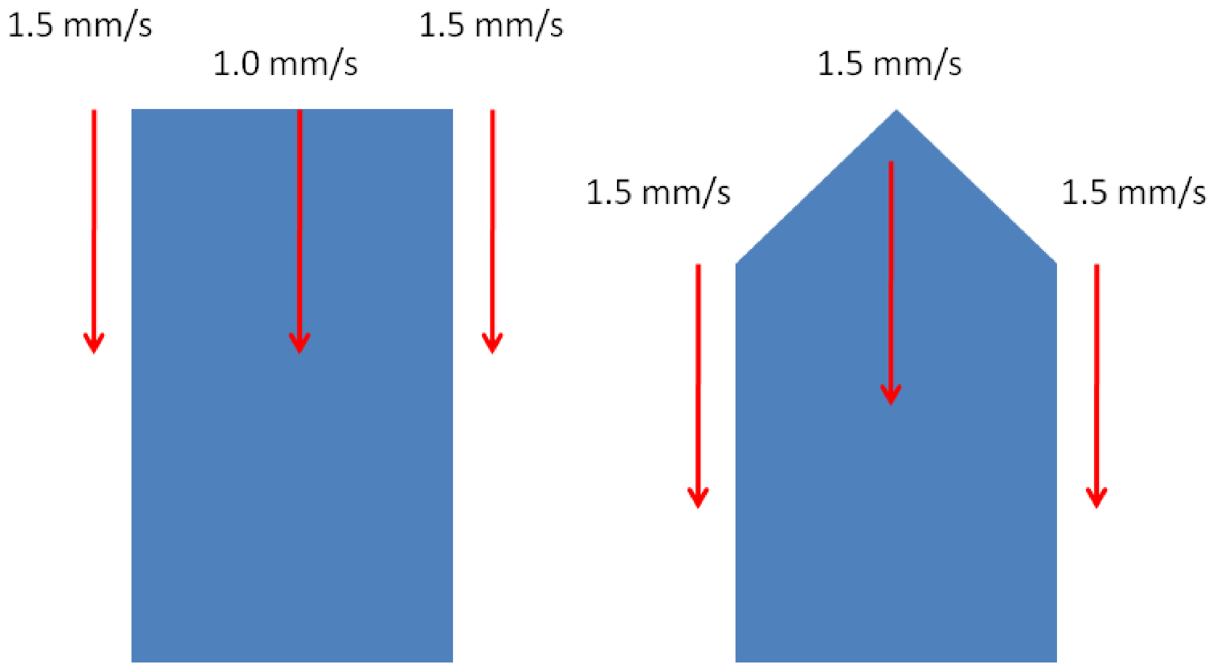

Figure 2: Summary of the velocity measurements. Figure 2-a (left) shows the beginning of the combustion. Figure 2-b (right) shows the steady state.

5 Future work

In addition to the single base strands produced, samples with the same geometries were manufactured with a triple base formulation (containing nitroguanidine, nitroglycerin and nitrocellulose as energetic components). Combustion tests recordings have shown a similar burning surface shape but precise measurements have not yet been made. It is expected that the conclusions to be obtained with the single base case shall help in perfecting the method used to calculate the required quantities. The test shall also be repeated with other formulations to cover the widest relevant range of burning velocities (double bases, porous single bases and composite formulations will be explored).

It is also noteworthy that the shape of the burning front matches what has been obtained with other materials [10]. It is expected that a better understanding of the heat transfer between the combustion region and unburned material should explain the shape and angle obtained. Although these experiments have shown that obtaining the linear burning rate value requires some efforts in order to account for edge effects, the surface flame propagation information gained could prove important in fully characterizing more complex solid propellants combustion problems.

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