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Development of strand burner for solid propellant burning rate studies

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Abstract. It is well-known that a strand burner is an apparatus that provides burning rate measurements of a solid propellant at an elevated pressure in order to obtain the burning characteristics of a propellant. This paper describes the facilities developed by author that was used in his studies. The burning rate characteristics of solid propellant have be evaluated over five different chamber pressures ranging from 1 atm to 31 atm using a strand burner. The strand burner has a mounting stand that allows the propellant strand to be mounted vertically. The strand was ignited electrically using hot wire, and the burning time was recorded by electronic timer. Wire technique was used to measure the burning rate. Preliminary results from these techniques are presented. This study shows that the strand burner can be used on propellant strands to obtain accurate low pressure burning rate data

1. Introduction

A strand burner is an apparatus that provides burning rate measurements of a solid rocket propellant at elevated pressure. It was used to evaluate new propellant formulations and ensuring quality control for a large propellant production, due to its low cost, simplicity and ability to produce good results in a short time period compared to sub-scale and full scale motor [1]. For burning rate measurement, the length of the strand is the importance parameter to be measured, but the size and shape of the strand is less significant [2-3]. Actually, there were no specific lengths, size or shape for a strand in measuring burning rate. Donald et al. [4] reported that, the lengths of propellant strand did not have a significant effect on burning rates. While Matthew et al. [5] reported that sample size did not have a large affect on burning rates except for the smallest size tested, 3.2 mm square. Studies made by Nelson et al. [6] used the propellant strand which have circular cross-sectional area while several researcher [7-8] applied square shape. Strand surface usually burning inhibited with an external coating such as cured HTPB [2, 9], vinyl resin solution [6], bituminous compound [4] or water based acrylic paint [7] to protect from the heat of combustion and ensure the burning only occur in one dimensional or ‘cigarette type’.

Commonly, a strand burner has a mounting stand to mount the strand either horizontally [10-11] or vertically [12-13]. It also equipped with ignition and timing circuit. Work by Nelson et al. [6, 14-17] used nickel-chrome wire as an ignition wire. For the timing wire, Kirk et al. [16] used 30 S.W.G tin /lead (63/37). In order to simulate the condition of high pressure in a chamber of a rocket motor, inert gas such as helium, carbon dioxide, argon or nitrogen is used to pressurize the strand burner. Rodolphe et al. [2] reported that, there are no significant different in the burning rate resulted when applying these gases. Study made by several researchers [2, 6] used the high chamber pressure ranging from 40 atm to 360 atm for burning rate test. However, there were also some studies used low chamber pressure [18]. The information from low-pressure combustion commonly used to optimize a base bleed-propellant design for high-altitude projectile [19-20]. The previous studies showed that, varying chamber pressures will give different burning rate [21-23]. The objective of this work is to determine the effect of chamber pressure to the burning rate of aluminized AP/HTPB propellant and along the way establishing the strand burner facility. The scope included measuring burning rate using the strand burner for five different chamber pressures ranging from 1 atm to 31 atm.

2. Methodology

2.1. Facility hardware

The strand burner in figure is designed for combustion of a propellant strand in continues gas flow up to 31 atm. The body, flange and both end cap are made of low carbon steel. The 23 cm long cylinder has an inner diameter of 10 cm and an outer diameter of 13 cm, offering a wall thickness of 1.5 cm thickness. Each end cap is 1.5 cm thick, making the overall length of the burner 26 cm. Both end caps are square with side length of 21 cm. A 1.2 mm black gasket was inserted between the end caps for a gas tight seal.

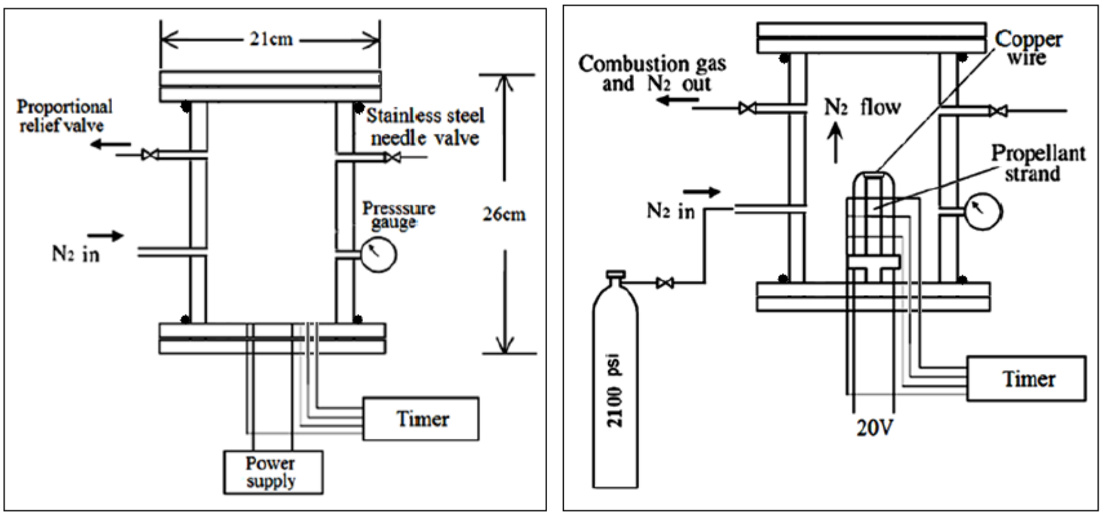

Figure 1. Schematic diagram of the strand burner facility

The strand burner was pressurized using nitrogen gas, which is same as the working fluid used by Shigeyuki et al. [24]. Nitrogen was chosen due to its low cost, availability and low density relative to air. Nitrogen gas was supplied from 22100 psi nitrogen tank at a suitable rate of flow. This will pressurize the burner as well as allowing steady flow of nitrogen at the outlet. Measurement of pressure within the strand burner was made by using a standard bourdon-type pressure gauge. At one of the end cap, there is a mounting stand used to mount the propellant strand. It was made from 5mm low carbon steel nut as shown in Figure 2.

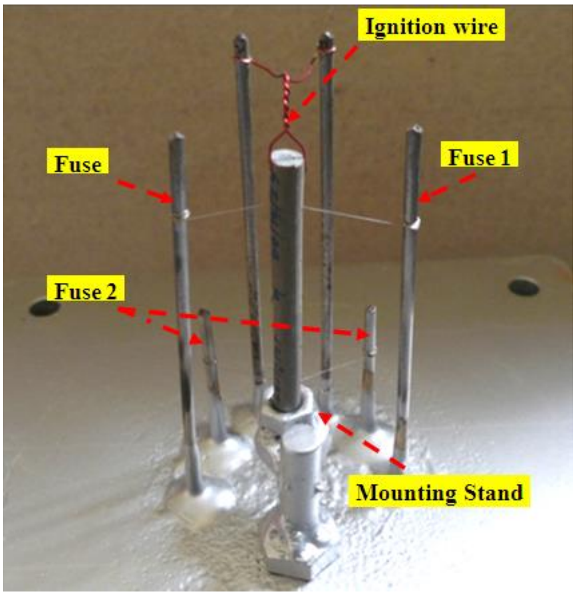

Figure 2. Example of propellant strand mounting

Around the mounting stand, there are six stainless steel rods with a diameter of 2mm which were used to hold wires/fuses for ignition system and instrumentation timer. The attachment between the rod and the end cap was air sealed using epoxy glue. To ensure the propellant strand could stand firmly and withstand the inlet and outlet flowing of the gas, the end of it was wrapped with white tape. During the experiment, the chamber pressure increased slightly due to combustion effects, and heat released. To stabilize it, two relief valves were installed at the upper end of the strand burner.

2.2. Propellant Selection

In this study, four specific propellant formulations have been selected for study. Table 1 present these four formulations where each propellant comprises a multimodal ammonium perchlorate (AP) as an oxidizer fraction, aluminum powder and HTPB binder. The first formulation, p60 subsequently referred as the baseline propellant, consists of 60 percent (by mass) AP and 25 percent aluminum powder. The O/F ratio (the ratio of AP fraction to the binder and aluminum fraction) is 1.5. The next three formulations were formulated by varying the O/F ratio to study their effect on the burning characteristics of aluminized propellant.

All propellants were manufactured manually at the Universiti Teknologi Malaysia (UTM) Propulsion Laboratory. To ensure safe practice, all propellants were prepared in 100gram batches. After finish the mixing procedure, the next step is to pressed the mixture into the soda straws, similar works as reported by Howard G. Cutforth [25]. The soda straws have 6mm diameter and they were cut to a length of 80mm. The strands were then transferred to the oven and cured at 64˚C for five days. The strands were visually inspected and were rejected if cracks, pores, or shape irregularities were seen.

Table 1. Formulations of the propellants.

Propellant	AP (%)	AL (%)	HTPB (%)	O/F
p80	80	5	15	4.00
p74	74	11	15	2.84
p66	66	19	15	1.94
p60	60	25	15	1.50

2.3. Procedure of testing

Wire technique was used to measure the burning rate. Three small holes were accurately placed along the strand length using a needle. An igniter and two fuses wires were passed through these holes and connected to a power supply and electronic timer respectively. Similar method was applied by Jolley [26] which used two fuses wire threaded through the propellant strand, while Clark [27] used three fuses wire. All wires used were of the same type of 38 S.W.G. tinned copper wire with 0.152mm thickness, this is the same type of igniter wire used by Rodolphe et al. [2]. The strand is mounted vertically and is ignited at the top end using electrical current. Depends on the resistance of igniter, it took about 1 to 2s to ignite. No inhibitor is used on the side faces of the propellant similar with the work done by several other researchers [15, 28]. The burning rate was measured by using electronic timer. It was determined from the period it took for both fuses separated at a distance of 50 mm apart to cut-off as shown in figure 3.

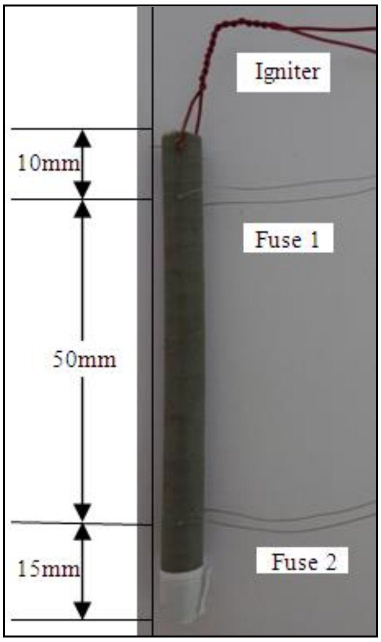

Figure 3. Propellant strand

The electronic timer was integrated with Data Acquisition Device (DAQ) in acquiring and recording the data [29]. The LabVIEW® software was then being used to analyze the data acquired as shown in figure 4.

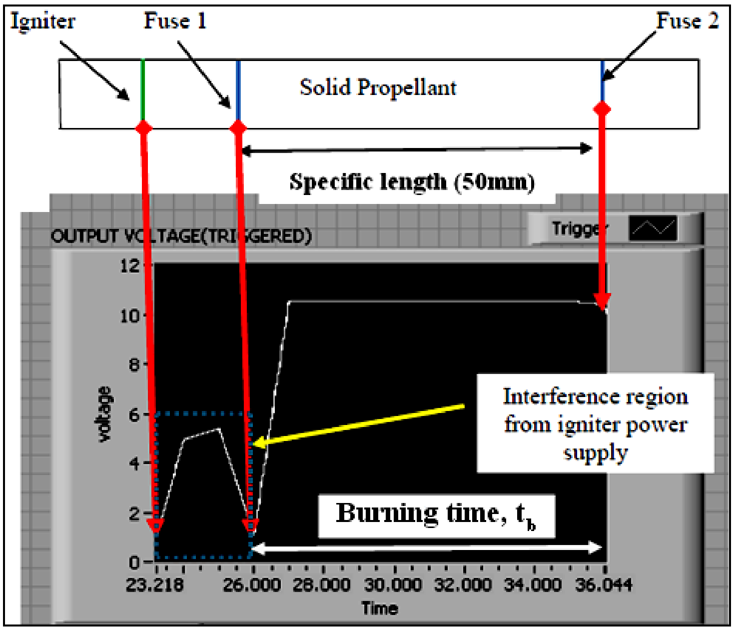

Figure 4. Actual burning time of the solid propellant at specified length.

$$r = \frac{L_p}{t_b} \qquad (1)$$

Where,
L_p = Specific propellant length, (mm)
t_b = Burning time from recorded data, (sec)

3. Result and Discussion

The strands were burned at six different combustion pressures ranging from 1atm to 31atm. Generally, three strands established the burning rate at a single pressure level and repeatability of the burning rates was observed within 5% and is acceptable according to Jayaraman et al. [30]. From the observations, the increase in pressure inside the strand burner was on average about 20% of the initial pressure and the burn rates were assigned to pressures equaling half the pressure rise added to the initial level as mention by Matthew et al. [9]. Throughout this study, nitrogen gas was allowed to flow slowly past into strand burner in order to prevent possible preheating of the strand by reverse flow of the hot combustion products and also to prevent the flame from flashing down the side of the strand as mention by Summerfield et al. [3]. Table 2 shows the average burn rate for the selected compositions.

Table 2. Average burn rate for four selected composition.

Propellant	1 atm	11 atm	21 atm	31 atm
p80	1.776	6.684	10.045	11.991
p74	1.630	6.113	9.520	10.749
p66	1.565	5.343	8.249	9.944
p60	1.527	4.610	7.327	8.425

3.1. Uncertainty Analysis for Burning Rate Test

Consider the calculation of burning rate from p80 at $\left(r = 1.776\,\mathrm{mm\,sec^{-1}}\right)$ 1atm,

$$r = \frac{L_p}{t_b}$$

Where, L_p and t_b are measured as;

$$L_p = 50\,\mathrm{mm} \pm 1\,\mathrm{mm}$$

$$t_b = 28.153\,\mathrm{sec} \pm 0.010\,\mathrm{sec}$$

The sensitivity of electronic timer is 1/1000. However, the burning time is taken to 1/100, considering a worst case condition. Thus, by taking the worse possible variations in propellant length and burning time, the error analysis could calculate as follows;

$$r_{\max} = \frac{(50+1)\,\mathrm{mm}}{(28.153+0.010)\,\mathrm{sec}} = 1.811\,\mathrm{mm\,sec^{-1}}$$

$$r_{\min} = \frac{(50-1)\,\mathrm{mm}}{(28.153-0.010)\,\mathrm{sec}} = 1.741\,\mathrm{mm\,sec^{-1}}$$

Thus, according to the method suggested by Holman [31], the uncertainty in the burning rate is $\pm 1.97\%$.

4. Conclusion

This paper has described the equipment being used in an intensive study of burning rate characteristics of ammonium perchlorate based solid propellant in order to get a better understanding on the effect of varying combustion chamber pressure to the burning rate. A strand burner has been developed which is capable of holding the surface of a burning propellant strand in pressurized condition. With this constrains satisfied, the burning rate of a propellant can be successfully investigated.

Acknowledgments

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