Experimental Investigation of a Regression rate On Hybrid Rocket Engine

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Abstract

Hybrid rocket had many advantage with compared to solid and liquid rockets. However, the engines have not yet been used in practical rocket systems, due mainly to the disadvantage of hybrid combustion, such as low fuel regression rate. In this study, lab-scale hybrid motor was designed and manufactured. And the methods of regression rate improvement were considered. Test firings with thrusts up to 300 N were conducted with GOX and transparent PMMA.

Thrust was calculated with the pressure of the combustion chamber and the regression rate was measured in with variation of oxidizer flow rate. The regression rates showed a strong dependency on GOX mass flux. The frequency analysis technique of the bulk-mode oscillation of motor was applied to a hybrid rocket motor and was based on the principle that this frequency was inversely proportional to the square root of the chamber volume. Several problems and solutions of operating hybrid rocket were presented.

Introduction

A rocket propulsion system in which one of the two propellant components is in liquid phase and the other is in solid phase is a hybrid rocket motor. The combination of a solid fuel and a liquid oxidizer is the most common one. In hybrid motors the solid fuel regression rate, a very important design parameter, is dependent on operating variables such as mass flux, pressure, properties of fuel and oxidizer, and fuel grain geometry.

For hybrid motors, most of the presently projected fuel and oxidizer combinations in their basic form have fuel regression rate around 1.5 mm/s or less under motor operating conditions. This low regression rate of solid fuel is the basic problem that degrades the application of hybrid motors. To address this issue, many studies have been conducted in recent years. Korting et al.[1)] observed that a rearward-facing step could have a noticeable effect on combustion behavior, increasing the regression rate by changing the profile of the burned fuel grain. Strand et al.[2)] supported the inclusion of particulate additives in solid fuel as an approach to enhance fuel regression rate.

The present study, with a primary goal of investigating the methods of regression rate enhancement, reports the results of a systematic investigation conducted at around 240 kg/m^{2}s mass flux condition. PMMA/GOX propellant combination was adopted for the study because PMMA fuel is apparent. And the comparison of the analysis of pressure transducer signal and the real time measurement of fuel grain are presented. This analysis of pressure transducer signal is based on the principle that the frequency of the bulk mode oscillation decreased in a predictable manner as the port diameter of the grain increases during the burn.

Experimental Procedure

A simplified schematic of the facility used for the experiment is shown in Figure 1. It consists of a gaseous oxygen delivery system, an ignition system and a combustion chamber. The oxygen supply is from a bank of cylinders kept at a maximum pressure of 10.0 MPa. A solenoid valve is used to initiate and terminate the flow of oxygen and is controlled by the PLC control unit. A sonic nozzle in the line maintains a desired constant mass flow rate. Nitrogen is used as a purge gas to terminate combustion after the desired burning time. The pressure maintained upstream of sonic nozzle is always kept higher than two times the maximum pressure of combustion chamber, so that the oxidizer mass flow rate is constant during the entire test.

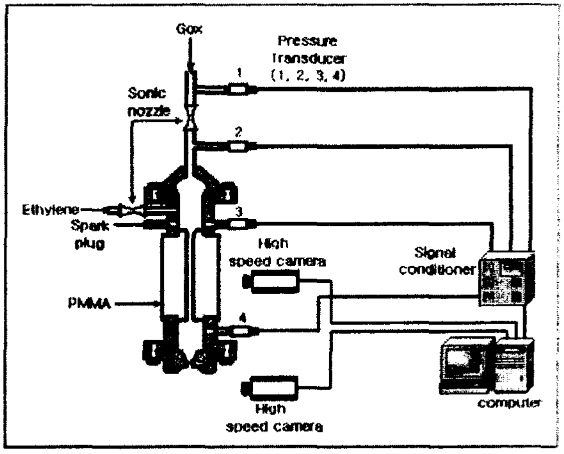

Fig. 1 a schematic of Hybrid motor test facility

The 160mm-long fuel grain is located within the stainless steel combustion chamber. The grain had an inner diameter of 12mm. A converging copper nozzle, the throat diameter of which is 8.5mm to provide the desired chamber pressure, constricts the downstream end of the combustion chamber. These copper nozzles could withstand a maximum firing duration of 8 s for

PMMA fuel grain. Figure 2 shows hybrid motor assembly.

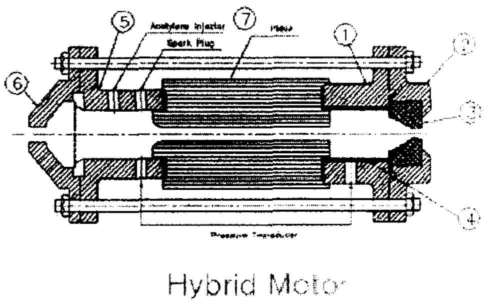

Fig. 2 Hybrid motor assembly

Each test run included the following steps. By suitable setting of the oxygen solenoid valve-opening period, a constant supply pressure of GOX was maintained upstream of the sonic nozzle. After the flow became steady, the igniter train was initiated. After the desired burn time, oxygen supply was cut off and nitrogen purge was opened to extinguish combustion. Combustion was initiated by heating the main oxygen flow with an igniter system that consisted of an ethylene gas flow and one automobile spark plug.

The test measurements were the image recording and the pressures: upstream and downstream of sonic nozzle, at pre and aft combustion chamber, and at ethylene injector. All of the signals from pressure transducers were recorded using 16-bit data acquisition system. The sampling rate was 1000 samples/s. For each test, the desired oxygen mass flow rate could be obtained by choosing an appropriate sonic nozzle throat and its upstream pressure.

A video camera and digital high speed camera were also used to observe the engine and exhaust plume during the test firings. For some of the firings, polarized filter was placed over the video camera lens to enhance flow visualization in the fuel grain port. A typical plume from the hybrid rocket is shown in Figure 3.

Fig. 3 Typical plume

Result and Discussion

To investigate PMMA regression rate behavior, a series of tests was conducted at different GOX mass fluxes and chamber pressure levels. Figure 4 shows a typical pressure time trace from the hybrid motor.

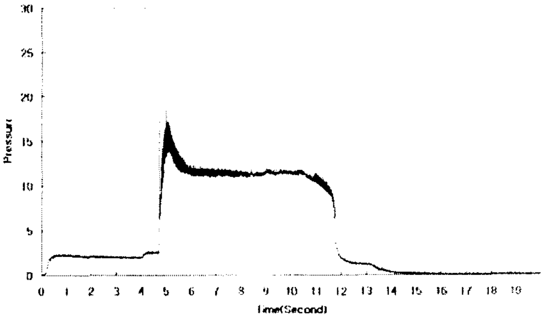

Fig. 4 Pressure-time traces of hybrid motor testing.

The solid fuel is ignited at 4.8 s, corresponding to the first rise in pressure registered by the transducer after the start of oxygen flow at 0 s. During about 5 s, oxygen supply pressure became stable. The fuel burned for 6 s, after which time the oxygen valve was closed. The aft combustion chamber pressure then began to drop as combustion ceased. The oxygen flow rate was 0.02717 kg/s and the average chamber pressure was about 1.15 MPa for the test. The average pressure is only concerned with the quasi-steady-state part of pressure signal, beginning immediately after the ignition pulse stabilized and ending immediately prior to the initiation of shutdown.

During the igniter operation, evidently due to the significant igniter mass flow contribution to the total flow, the chamber pressure is about 1.6 MPa higher than the equilibrium chamber pressure.

Thrust might be calculated approximately with the averaged chamber pressure like below:

$$F = \left[\Gamma \sqrt{\frac{2\gamma}{\gamma-1}\left\{1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right\}} + \frac{A_e}{A_t}\left(\frac{P_e}{P_c}-\frac{P_a}{P_c}\right)\right] \times P_c \times A_t$$

(1)

For the oxygen flow rate of 0.0226 and 0.02717 kg/s, calculated thrust was about 55 N and 84 N respectively. These values were approximately same value compared with designed thrust values.

Zilwa et al.$^{3)}$ presented a novel technique for determining the instantaneous spatially-averaged port diameter of solid fuel grains in hybrid rocket motors using measurement of the frequency of the bulk-mode oscillation of the motor and was based on the principle that this frequency was inversely proportional to the square root of the chamber volume. A Helmholtz oscillation can occur whenever a large volume terminates in a narrow throat. Bulk mode occur due to the alternating compression and relaxation of the large volume by the fluid in the narrow throat and the natural frequency of this oscillation can be calculated as

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{Vl}} \tag{2}$$

The volume of the fluid that is compressed by the fluid in the nozzle throat, and hence that used to calculate the bulk-mode frequency, is equal to the sum of the fuel grain port volume and the combustion chamber volume.

This frequency decreased monotonically as the port of the fuel grain opened up during the burn as can be seen from Figure 5.

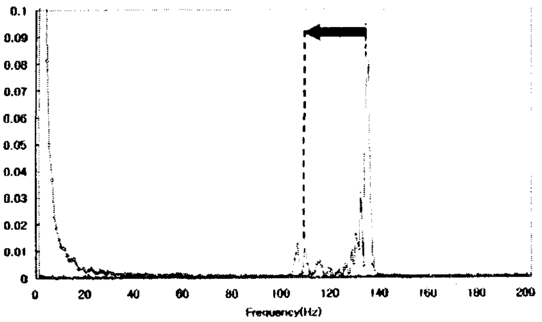

Fig. 5 Variation of pressure spectrum with time

Each spectrum was obtained over 1-second internal and there was a 1-second shift between adjacent spectra.

Figure 6 represents the curve obtained from equation (2), using pressure spectrum with time for the initial fuel grain port diameter of 12mm. The profile of instantaneous port diameter calculated at 0.5 s intervals for one of tests. The regression rate could be deduced as the slope of this curve and it was clear that it decreased as the burn progressed. In ignition operation period, 6-7 second, it is shown that regression rate is higher than main burning region. This is due to the igniter mass flow contribution to the oxygen flow.

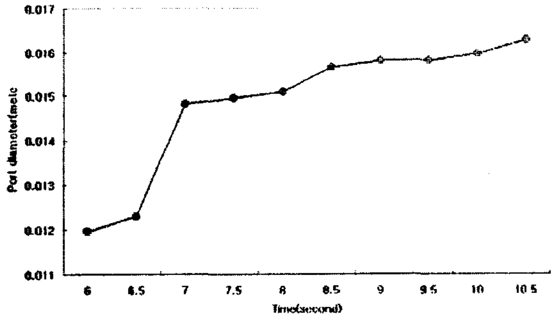

Fig. 6 Instantaneous port diameter

The most important measurement in characterizing a hybrid rocket propellant is the spatially averaged regression rate of the solid fuel grain. Usually the regression rate is determined as a time averaged value from the mass lost from the grain during the burn, with correction for the ignition and shutdown transients. In present study, apparent PMMA solid fuel was used. Therefore, the fuel port diameter variation could be observed in real time.

A commercial video camcorder was used to record the instantaneous fuel port diameter variation throughout burning time. Shutter speed was 1/4000 s and circular polarized filter was placed over the lens to prevent blur images by the bright self-luminous plume in the fuel grain port. From the acquired image, instantaneous port diameter could be measured by using simple image process tool.

The spatially averaged instantaneous port diameter vs burning time for the frequency analysis with pressure transducer signal and the real time acquisition with video camcorder are shown in Figure 7

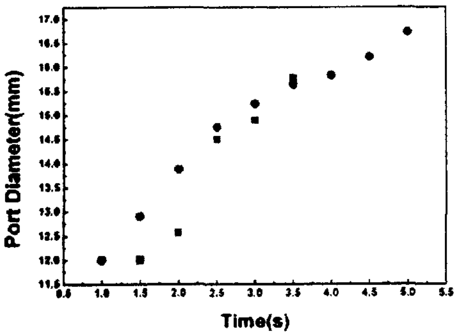

Fig. 7 Port diameter variation of frequency analysis and real time acquisition

Circular symbols represent the real time measurement of fuel grain and the other represent frequency analysis results. There were also some errors in initiation region because of ignition transient.

The spatially averaged instantaneous regression rate vs oxidizer mass flux for PMMA grains are shown in Figure 8. In the present study, the maximum oxidizer mass flux was below 240 kg/m^{2}s. The regression rates are relatively high at the beginning of the test, but decrease continuously with mass flux decrease due to the increase in the local port area and corresponding decrease in the local mass flux.

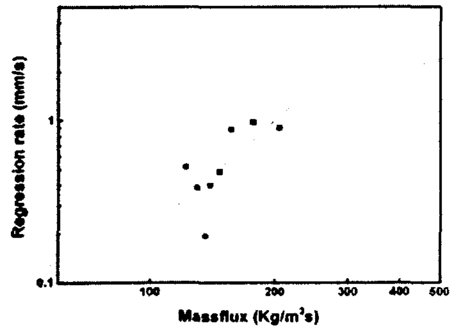

Figure 8. Regression rates of PMMA grain

The research of regression rate for PMMA fuel grain is in progress. Therefore the regression rate correlations for PMMA hybrid rocket are developed after several series of test conducted. However, an average regression rate could be estimated simply. In the case of the oxidizer mass flow rate of 0.02717 kg/s, an average regression rate of 0.68mm/s was observed. Figure 9 shows PMMA fuel grain features before and after the test run.

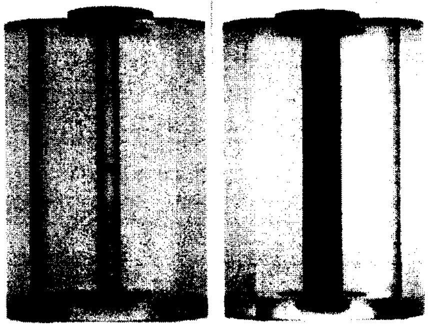

Figure 9 Photographs of PMMA fuel grains.

Conclusion

A series of hybrid engine test firings was conducted to investigate regression rate and combustion behavior over a range of operating conditions. Major results of the investigation include:

1) We designed lab-scale hybrid rocket motor. And we completed the hybrid test facility.

We can perform stably many combustion test

2) When oxidizer mass flow rate is 0.02717 kg/s, average of regression rate is measured to 0.68 mm/s.

3) Fuel grain port diameter change is estimated to pressure transducer signal analysis. It is agreed comparatively with real value.

Further Research

It is suggested that further research be conducted on the regression rate correlations of PMMA fuel over a range of oxidizer mass flow rate and on the effects of the swirl injection of oxidizer.

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