Development of Pyrogen Igniter for Kick Motor

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Keywords: Kick Motor, Pyrogen Igniter, Ignition Delay Time

Abstract

A pyrogen igniter was designed to satisfy the required condition of kick motor system for the space launch vehicle. We analyzed the ignition characteristics and performed the combustion tests to verify the internal ballistic performance. In the design process, the arc-image test was carried out to find the sufficient heat flux as varying the initial pressure from 10 to 700kPa. The analysis indicated that the initial pressure condition would delay ignition time within a range from 100 to 500ms. The combustion test with an inert chamber was also performed to understand the ignition characteristics with the variation of the initial pressure of free chamber volume. Finally, we confirmed that the igniter could provide the acceptable energy to ignite the propellant of kick motor at the ground test. The result of the ground tests showed that the ignition delay time was within the design range at the atmospheric pressure condition.

Introduction

The principal role of the igniter is to provide the necessary energy to the propellant which will result in a steady-state combustion.1, 2) A pyrogen type igniter was designed to satisfy the required condition of kick motor system for the space launch vehicle. The pyrogen igniter is essentially a small Solid Rocket Motor (SRM) within a larger SRM, and have the advantage that provides a sustained high-temperature flame.3) In the designed igniter, the booster charge which consists of powder and pellets, propagates explosive train from the initiator of Safety & Arming Device (SAD) to the igniter propellant grain as shown in Fig. 1. Combustion product flowing through the nozzle exit of the igniter, penetrates on the surface of the kick motor grain, and transfers sufficient energy for steady-state combustion of kick motor during the ignition event.4)

The specification of the igniter was determined on the basis of the empirical relation and analysis. Then, we analyzed the internal ballistics and predicted the ignition delay time under the operating condition. The arc-image test was carried out to find the sufficient heat flux for the ignition of the kick motor propellant as varying the initial pressure. The combustion test was also performed with an inert chamber to understand the ignition characteristics with the variation of the initial pressure of free chamber volume. Finally, the ground tests were performed to confirm that the igniter could provide the acceptable energy to ignite the propellant of kick motor.

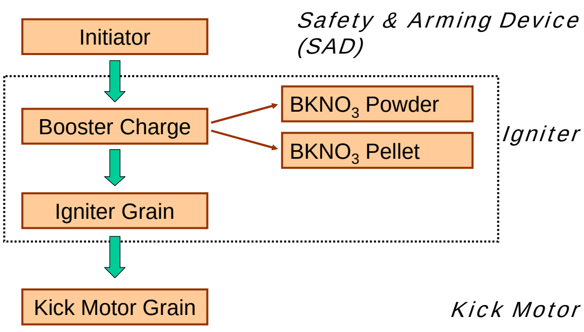

Fig. 1 Ignition Train

Design and Development of Igniter

Design Parameter and Ballistic Performance

The igniter consists of head, case, retainer, insulation, propellant, liner, booster charge, pellet holder, and so on. The igniter head is attached to the front boss of the kick motor case with bolts, and is sealed with O-rings to prevent to gas leakage during the whole motor operation. The head is also mated with two SAD and the pressure sensor device. The case contains the igniter propellant, and prevents the environmental contamination during the storage and transportation process. The insulation is applied to the igniter head and case to protect the igniter from the high operating pressure and temperature combustion products. The propellant is the HTPB (Hydroxyl Terminated Poly-butadiene Polymer) type propellant with high burning speed. The liner is used to attach the propellant to the igniter case. A pellet holder is filled up with the powder and pellet-type booster charge made of BKNO3, and is mounted into the igniter head.

Among the design parameters of the igniter, the ignition delay is affected by the composition and flow rate of the igniter gas.5, 6) Therefore, the determination of igniter charge mass is the important process for the igniter design. The burning time of the igniter is usually in the range of 0.1 to 0.5 sec. The mass flow rate of the igniter per unit area of initial propellant surface is typically 1 kg/sec-m^2. Since the initial propellant surface of the kick motor is approximately 1.988 m2, the mass flow rate of igniter is 1.988 kg/sec empirically.

The prediction indicated that the maximum pressure was 8.3 MPa after the igniter initiated as shown in Fig. 2. The igniter pressure remained approximately constant over 8.0 MPa for 0.3 sec, and then fell to an end at 0.6 sec. The propellant grain was designed as the wagon wheel shape where the combustion gas provided at a constant flow rate during the web burning time to achieve a neutral pressure-time trace. The mass flow rate of the igniter was about 1.955 kg/sec for the first 0.3 sec after the igniter initiated, its value is close to the empirical relation about the calculation of the propellant mass.

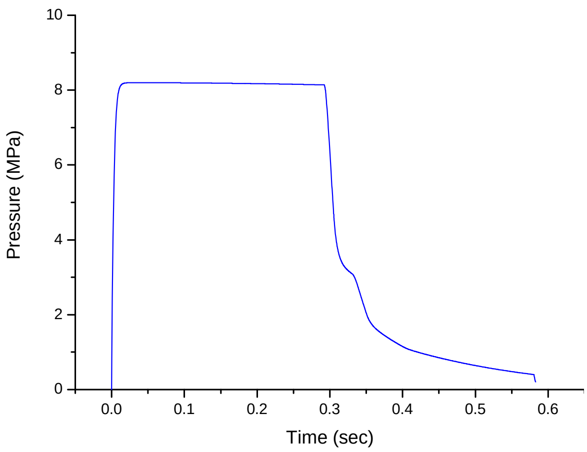

Fig. 2 Prediction of Internal Ballistics of Igniter

Arc-Image Test

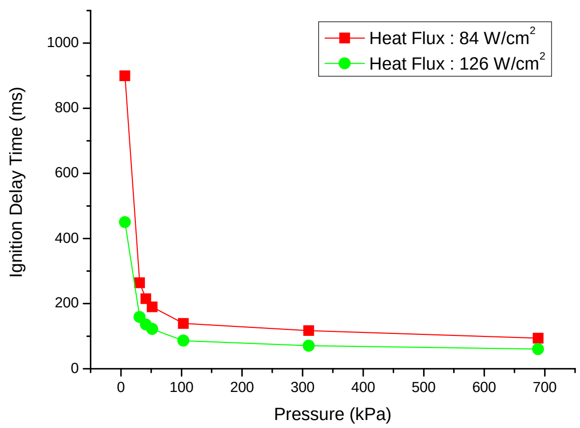

Fig. 3 Ignition Delay with Various Heat Fluxes at Arc-Image Test

The ignition of the kick motor propellant is dependent on the pressure and heat flux produced by the igniter. Fig. 3 shows that the ignition delay is longer than 1 sec at the pressure below 5 kPa even though the heat flux is high (126 W/cm^2). At the extremely low pressures, ignition does not occur because of rapid diffusion and dissipation of the decomposition gases.[7] On the other hand, as pressure is increased above atmospheric pressure, the ignition delay time is hardly affected by pressure. For many propellants, a pressure-independent regime occurs in the range 300 to 700 kPa. Therefore, the igniter was designed to provide the sufficient heat flux larger than 84 W/cm^2 into the kick motor propellant for 200 ms at atmospheric pressure.

Prediction of Ignition Delay Time

The ignition delay time is defined as the interval between the first ignition signal and the beginning of steady state thrust.[5] The composition and flow rate of the combustion gas of the igniter have an effect on the ignition delay time. The ignition characteristics is also dependent upon the design parameters of the kick motor, such as the geometry of the propellant grain, the initial free volume of motor chamber , the nozzle shape, the initial pressure of motor chamber before ignition, the burst pressure of nozzle closure, and so on. Because propellant ignition energy requirements at low pressures are strongly dependent on pressure, it is important to attain an established pressure in the motor chamber during ignition process for the kick motor operating at high altitude.

The ignition delay time of the kick motor is described by four steps as shown in Fig. 4:

θ_1 : the response time of the igniter after initiation signal

θ_2 : the time interval from initiation of the igniter until the burst of nozzle closure

θ_3 : the time interval between the burst of nozzle closure and the ignition of the main motor propellant

θ_4 : the time interval where the motor pressure reaches 90% of the designed pressure

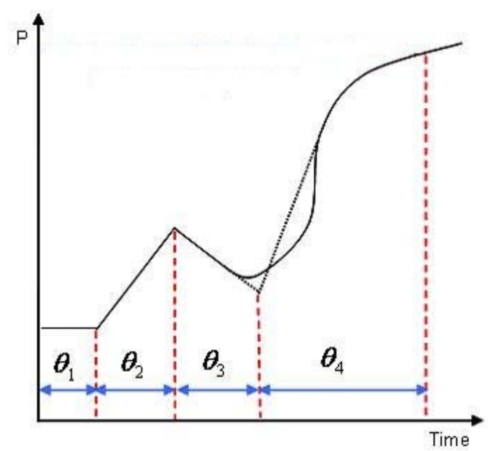

Fig. 4 Ignition Pressure Transient

Assuming that the nozzle closure is attached to the kick motor, the ignition delay time is calculated by considering thermal balance and mass conservation.[1,8] Fig. 5 shows that the results of the prediction of the ignition delay time when the initial pressures of motor chamber are atmospheric pressure (101.3 kPa) and vacuum condition.

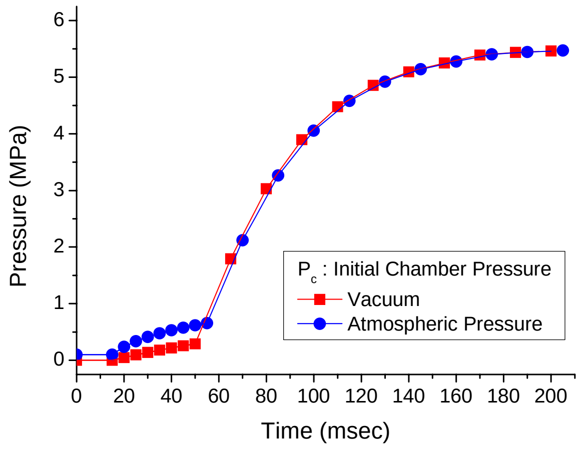

Fig. 5 Prediction of Ignition Characteristics with Initial Chamber Pressure

The first time step, θ_1, is caused by the delay of the initiator and the booster charge after initiation signal. In the prediction, the first step, θ_1 is assumed to be less than 15 ms. The second time step is the period between the initiation of the igniter and the burst of nozzle closure. The prediction shows that θ_2 is 40 ms when the initial chamber pressure is atmospheric pressure, however the θ_2 is 32 ms when the initial chamber condition is vacuum. The time until the motor propellant reaches to the auto-ignition temperature is calculated to decrease as the initial chamber pressure gets lower. The third step is seldom observed in the applications of conventional motors. However, rapid changes in the internal rocket motor flowfield can occur due to nozzle closure removal in the case of a sufficiently long motor, e.g., the space shuttle SRM.[9] This step can be neglected if the burst pressure of nozzle closure is assumed to be higher than the ignition pressure of main motor propellant. The fourth time step, θ_4, is calculated to be 130 ms for the atmospheric pressure condition, and 145 ms for the vacuum condition.

The total ignition delay time for the atmospheric condition is 185 ms, shorter than that for the vacuum condition (192 ms) even though the main motor propellant initiates rapidly at the vacuum. The pressure when the surface of main motor propellant ignites is calculated to be more than 290 kPa. Hence, the burst pressure of nozzle closure is set to 345 kPa to attain the reliable combustion of the motor propellant before the nozzle closure removal at ground and high-altitude conditions.

Test Results and Discussion

Combustion Test

An inert chamber was manufactured to carry out the performance test of the igniter as shown in Fig. 6. The inert chamber has the same geometry with the initial free volume of the kick motor grain. Hence, we could investigate the igniter performance with respect to the characteristics of initial pressurization and chamber filling during the ignition transient process.

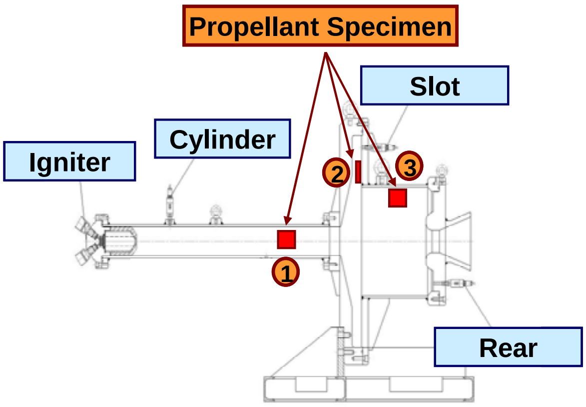

Fig. 6 Inert Chamber Configuration

Table 1 Test Matrix for Performance Evaluation

Test No.	Initial Pressure (kPa)		Propellant Specimen Attachment
	Igniter Case	Inert Chamber	
#1	101.3	101.3	×
#2	2.7	2.7	×
#3	101.3	101.3	○
#4	101.3	1.3	○
#5	2.7	2.7	○

The igniter was mounted into the front port of the inert chamber, and the pressure sensors were placed at the igniter head. The pressures of the inert chamber were measured at the cylinder, slot, and rear position. The propellant specimens were attached to the inner wall of the inert chamber to determine whether the igniter could provide the sufficient energy for the ignition of the motor propellant. The igniter #1 and #2 were tested with the different pressures of the initial chamber as shown in Table 1.

Fig. 7 The Combustion Test of the Pyrogen Igniter with an Inert Chamber

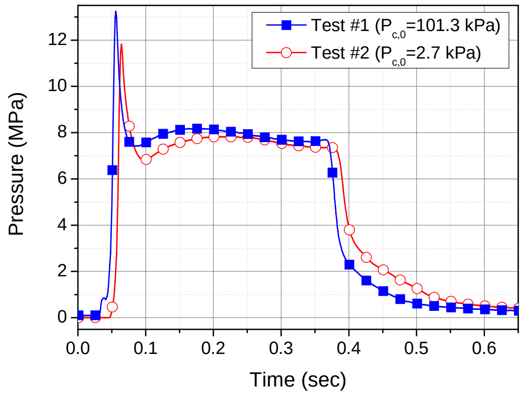

Fig. 8 Comparison of Igniter Pressure (Head-End Pressure) History with Different Initial Chamber Pressures

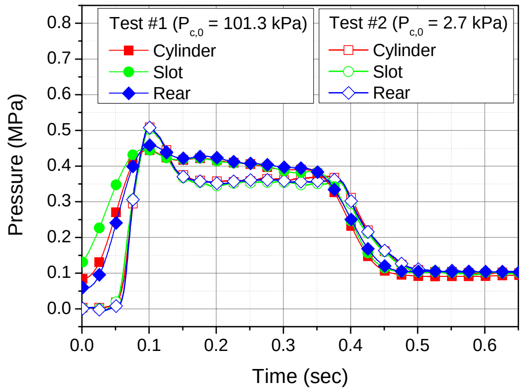

Fig. 9 Comparison of Chamber Pressure History with Different Initial Chamber Pressures

The pressures of the igniter #1 and #2 started to rise at 36 and 52 ms after initiation signal, respectively. The igniter #1 at the atmospheric condition was initiated slightly faster than the igniter at the low initial pressure condition. However, the pressures during the web burn time from 0.1 sec to 0.4 sec did not show the significant difference with respect to the initial condition of the inert chamber.

Fig. 9 shows that the pressure of the inert chamber was maintained by the combustion gas of the igniter during web burn time from 0.1 to 0.4 sec. When the initial chamber pressure was low (igniter #2), the more mass flow was required to fill up the inert chamber until the chamber closure was removed.

When the closure is attached to the nozzle, the combustion product fills the free volume of the chamber and the pressure rises up to the established burst pressure of the closure. If the igniter operates without the closure, the pressure of the inert chamber increases as the mass flow rate of the igniter increases. The pressure of the inert chamber was predicted to be approximately 0.45 MPa when the mass flowrate of the igniter was 1.955 kg/s as shown in Fig. 10. Therefore, the designed igniter can supply the required pressure to ignite the propellant of the kick motor considering the arc-image results.

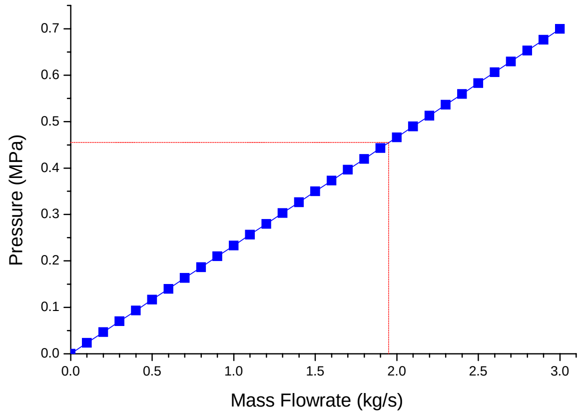

Fig. 10 Prediction of Chamber Pressure with Igniter Mass Flow Rates for without Nozzle Closure

The tests of the igniter #3, #4, and #5 were performed to investigate the heat flux characteristics varying the initial chamber pressures. The propellant specimens were found to be burned by the combustion energy of the igniter except for some specimens attached at the slot as shown in Table 2. In the geometry of the motor grain, the rear slot was away from the center axis of the combustion flow. Even though the pressure at the slot was similar to the pressures at other positions, the sufficient energy seemed not t be fully transferred to the propellant surface in the slot region when the surface of the motor propellant begins to ignite.

Table 2 Test Results of Propellant Specimen for Heat Flux

Test No.	Propellant Specimen		
	Position 1 (Cylinder)	Position 2 (Slot)	Position 3 (Rear)
#3	Burned	Unburned	Burned
#4	Burned	Unburned	Burned
#5	Burned	Burned	Burned

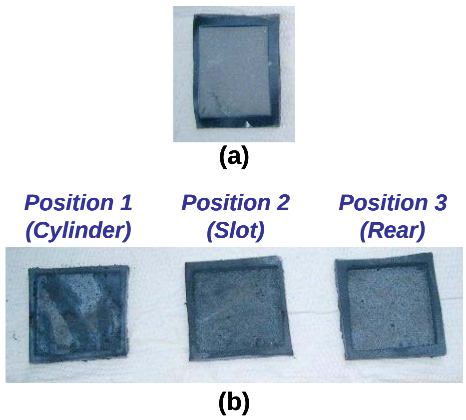

Fig. 11 Propellant Specimen for Measurement of Heat Flux (a) Test Specimen (b) Burned Propellant Specimen after Test #5

Ground Test

After the verification of the igniter performance, two types of real-scale kick motor tests were performed to ascertain that the igniter delivered the acceptable energy to ignite the motor propellant. One was the ground test with a shortened nozzle because of the separation at the nozzle expansion part, and the other was the high-altitude test with a flight-type nozzle. The diffuser was placed adjacent to the nozzle exit to simulate the high-altitude environment by making supersonic exhaust gas flow after ignition. We sealed the kick motor with nozzle closure before ignition, and did not consider the vacuum ignition. Therefore, the initial pressure conditions of two cases were the same: the igniter was initiated at the atmospheric pressure. The kick motors of both two cases were ignited normally, and operated successfully within the design conditions.

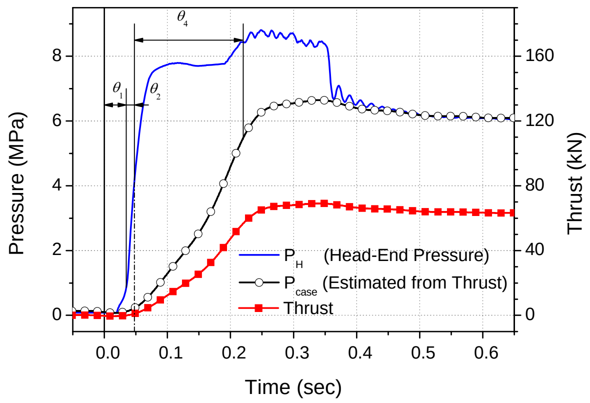

Fig. 12 Pressure and Thrust Development at the Ignition Transient in the Test of Real-Scale Motor A

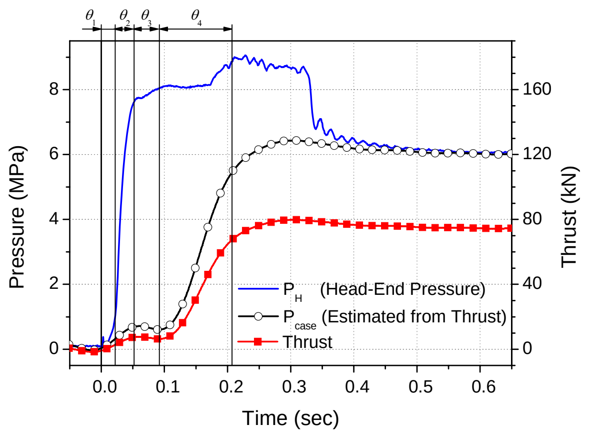

Fig. 13 Pressure and Thrust Development at the Ignition Transient in the Test of Real-Scale Motor B

Total ignition delay time was defined as the time when the case pressure of kick motor reached to 90% of the designed pressure. However, the motor case pressure could not be measured directly while the igniter operated, because the pressure sensors were mounted at the igniter head. Hence, the case pressure of kick motor, P_{case}, during the ignition transient process was estimated from strain gage readings and directly-measured thrust trace.10)

The case pressure of the motor A showed a continuous pressure rise after the burst of nozzle closure (2), while that of the motor B showed slight pressure decrease. Thrust and the estimated case pressure of the motor B showed the similar structure of the four-step ignition transient process as shown in Fig. 4.

In the sufficiently long motor such as Space Shuttle SRM, thrust is momentarily produced by the pressure wave encountering nozzle closure during chamber filling, and decays rapidly after flow through the nozzle is established.9) Because the diffuser was located at the nozzle exit plane of the motor B, the interaction of the pressure waves with the nozzle was significant at about the time of the nozzle removal. However, the total ignition delay times for the real-scale motor A and B were respectively 0.219 and 0.207 sec after the initiation signal. Hence, the diffuser for the simulation of the high-altitude environment did not affect the ignition characteristics and performance significantly.

Conclusion

We have designed an igniter for the kick motor and analyzed the ignition delay time. From the results of an arc-image test, the igniter was designed to provide the sufficient heat flux larger than 84 W/cm^2 into the kick motor propellant for 200 ms at atmospheric pressure. The mass flowrate and the weight of igniter charge were determined to ignite the motor propellant stably within the design condition. The combustion tests were carried out to investigate the performance of the igniter and the ignition characteristics with respect to the initial chamber pressure. The ignition delay was predicted to be approximately 200 ms, and was verified to ignite the motor propellant steadily at the ground tests.

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