Research paper

Combustion behavior of an ammonium perchlorate composite propellant motor during inert gas injection —Effective condition of water spray for interruption—

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Received: December 15, 2017 Accepted: August 1, 2018

Abstract

Some solid propellants have an intermediate self-quenching pressure range (ISQPR), which is around several MPa. When the propellants are burned in a motor under a pressure near the lower limit of the ISQPR, the motor exhibits oscillatory combustion. In a previous study, we attempted combustion interruption to pressurize the motor chamber from the oscillatory combustion state into the ISQPR. After pressurization by inert gas, water spray sometimes quenched the burning surface, but sometimes failed. We should clarify how the timing of water spray in the pressure oscillation aspect affects the interruption. In the present study, our objectives were to control the pressure oscillation aspect and to examine the relationship between the water spray timing in the controlled pressure oscillation and the interruption. An experiment revealed that the oscillatory aspect was controllable by adjusting the direction of inert gas injection. The timing of water spray had little effect, but holding the pressure around the higher limit of the ISQPR was effective for interruption.

Keywords: solid rocket motor, propellant, rocket propulsion, combustion

1. Introduction

For some rocket engine applications, such as soft landings and remaining on station, thrust modulation and combustion interruption are necessary. Solid propellant rocket motors have been widely used for a long time because of their good storability and simple structure. However, solid rocket motors have difficulties with respect to controlling thrust and terminating combustion.

Some propellants composed of unimodal fine crystalline ammonium perchlorate (AP) and a fuel-rich polymeric binder without metal fuel have a unique characteristic. Namely, the propellant cannot deflagrate in an intermediate pressure range of approximately several MPa[1]. This pressure range is called the intermediate self-quenching pressure range (ISQPR). Generally, the equilibrium pressure of a solid propellant rocket motor is determined by the balance between the mass flow rate generated from the grain and the mass flow rate discharged from the motor throat. Figure 1 explains the equilibrium pressure of the propellant, which has an ISQPR[2]. When such a propellant burns in a rocket motor, the generated mass flow rate appears as a discontinuous curve in the ISQPR. In the figure, the black solid curves are in deflagration ranges, and the broken lines indicate the deflagration limits. When the discharged mass flow rate is drawn as a blue line in the same figure, three intersections appear. At the highest intersection, the motor shows stable combustion due to the equilibrium between the generated mass flow rate and the discharged mass flow rate. At the lowest intersection, the motor shows the oscillatory combustion behavior due to the statistical occurrence of local extinction and reignition. The middle intersection is statically unstable because the pressure index exceeds 1, and the motor cannot maintain combustion at this point. The equilibrium state at higher pressure can be referred to as the high-mode state, and another equilibrium state at a lower pressure can be referred to as the low-mode state[2),3)]. In a previous study, we attempted to interrupt combustion by means of pressurization with an inert gas in order to maintain the

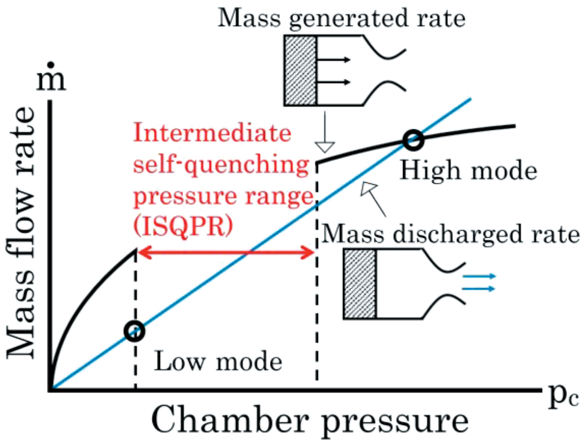

Figure 1 Pressure-dependent mass flow rates and equilibrium states in two modes.

chamber pressure within the ISQPR. When the chamber pressure was increased by inert gas to be in the ISQPR from low-mode state, the combustion was not interrupted but exhibited an oscillatory aspect. As such, the water spray was needed to complete combustion interruption. Although the interruption was sometimes completed, it sometimes failed[4]. We conceived that the direction of inert gas injection affects the pressure oscillation aspect and that the timing of the water spray in the pressure oscillation aspect affects the combustion interruption.

The objectives of the present study were as follows. We examined the effect of the direction of the inert gas injection on the chamber pressure oscillation. In addition, we then examined the effect of various timings of water spraying during the controlled chamber pressure oscillation on the entire surface extinction.

2. Experimental procedure

We used a composite propellant composed of 73% ammonium perchlorate and 27% hydroxyl-terminated polybutadiene in mass. The crystalline AP particles had a unimodal distribution with an average diameter of 15 μm. Figure 2 shows the burning rate characteristic of the propellant from the test of a strand burner, which used 7-mm-wide strand samples. The intermediate pressure ranged from 3 MPa to 8 MPa. Another detailed test involving a strand burner, in which 12-mm-wide strands were used and heat loss was reduced, showed that the ISQPR of the propellant was between 4 and 6 MPa[4].

Figure 3 shows the experimental setup. The end-burning grain diameter was 77 mm, and the web length was 20 mm. Nitrogen gas was used as inert gas. The chamber and the gas storage had its own pressure and temperature sensors. Inert gas injection and a water spray were controlled by ball valves, which were driven by a personal computer. The water spray nozzle was fabricated with eight holes to inject spray droplets uniformly onto the entire burning surface. The water was sprayed after the start of the chamber pressure oscillation, which occurred by inert gas injection. When we conducted experiments without water spray (Experiment A, described later), the bridge pipe was removed, and all of the inert gas was injected from the inert gas nozzle. The

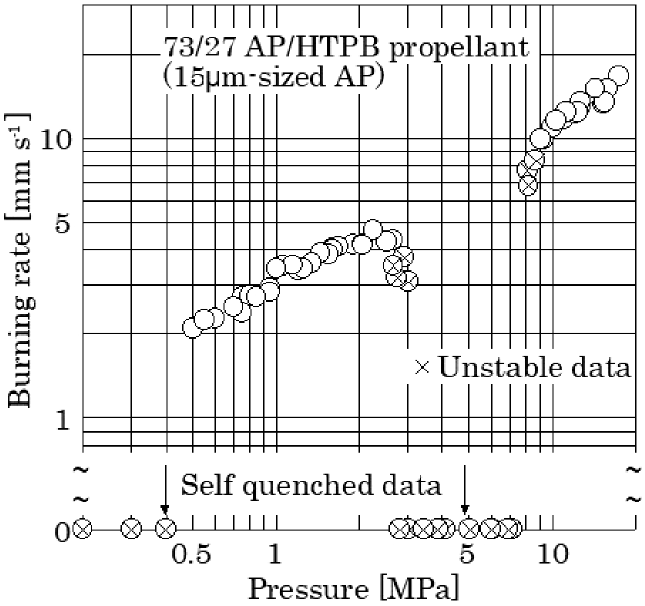

Figure 2 Burning rate characteristic of a self-quenched propellant from Reference (4).

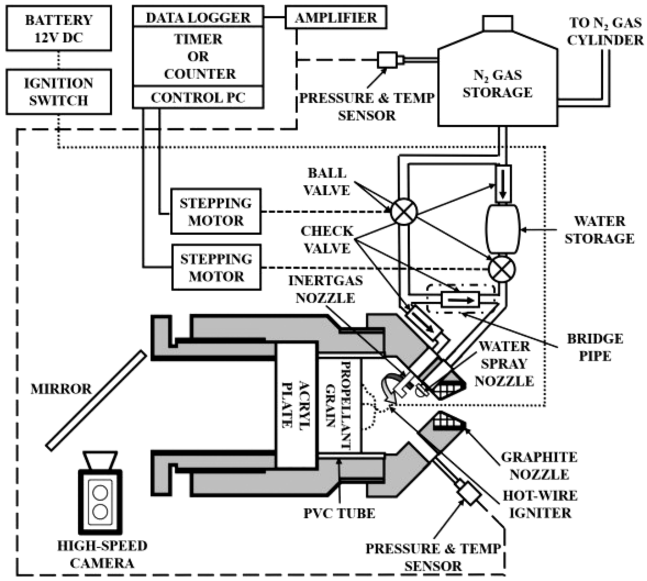

Figure 3 Schematic diagram of the experimental setup.

direction of the inert gas nozzle was adjusted before starting the experiments. The number of ports drilled through the motor case was limited. When we conducted experiments with water spray (Experiment B, described later), the water spray nozzle concurrently served as an inert gas nozzle directed toward the burning surface. Check valves prevented reverse flow of combustion gases through the inert gas nozzle. The flow rates of inert gas through the two nozzles were set to be approximately the same. The burning surface of the propellant was observed from the back of the propellant grain through an acrylic plate. The images were recorded by a high-speed camera with a frame rate of 1,000 fps.

Two types of experiments were conducted. Table 1 shows the conditions. Experiment A was conducted in order to clarify the effect of the direction of inert gas injection on the chamber pressure and the flame propagation. The direction of inert gas injection was to the throat or to the burning surface. The gas storage pressure

Table 1 Experimental conditions.

Exp.	Examined factor	Water spray
A	Direction of inert gas injection · to the nozzle throat · to the burning surface	None
B	Timing of water spray	Done (1.5 g)

was set to be 6.5 MPa in order to prevent the chamber pressure from exceeding the ISQPR. In conducting Experiment A, propellant was first ignited, and the motor established low-mode combustion. Inert gas was then injected into the chamber. Experiment B was conducted in order to interrupt combustion with a water spray. The examined factor was the timing of the water spray. Based on the results of Experiment A, the combustion pressure was made to oscillate distinctively at an increased pressure level within the ISQPR. We changed the timing of the water spray during a period of pressure oscillation and observed the combustion behavior. In conducting Experiment B, the propellant was first ignited, and the motor established low-mode combustion. Inert gas was then injected into the chamber, and the chamber pressure was made to oscillate appropriately. Water was then sprayed onto the burning surface at various timings with respect to the pressure oscillatory aspect.

3. Experimental results and discussion

3.1 Effects of the direction of inert gas injection on combustion

Figure 4 shows a typical pressure history and the corresponding burning aspects with inert gas injection toward the throat. The chamber pressure was not increased sufficiently to be in the ISQPR. The amplitude of the pressure oscillation became higher than that in the low-mode state. Whereas the amplitude of pressure oscillation was around 0.3 MPa before the gas injection, it was increased to 1.0 MPa after the injection. The entire burning surface flickered, and its aspect was synchronized with the chamber pressure oscillation. The pressure oscillation frequency was not changed by inert gas injection from the frequency of low-mode combustion and remained at around 5 Hz. The mass flow rate of the inert gas was nearly the same as the mass flow rate from the grain in the low mode. We conjectured that the average chamber pressure was not increased sufficiently due to the concurrent cooling effect of inert gas. Based on a previous experimental result, as the throat area was constricted in the low-mode combustion, the amplitude of pressure oscillation increased, but the average pressure did not vary[5)]. In the present experiment, cold inert gas would have made the apparent throat area narrow and interrupted the hot gas discharge through the throat without disturbing the burning surface.

Figure 5 shows a typical pressure history and the corresponding burning aspects with inert gas injection toward the burning surface. The chamber pressure sufficiently entered the ISQPR. The propellant continued burning, exhibited an oscillatory aspect. The amplitude of pressure oscillation during inert gas injection ranged from 0.3 MPa to 0.7 MPa. The frequency of pressure oscillation changed from 5 Hz to 20 Hz after inert gas injection. The burning surface did not flicker slowly over the entire surface, but flickered rapidly in discrete local areas. There was little difference on the burning surface during the pressure oscillation. Previous strand test showed that the propellant couldn't burn when the pressure was increased by inert gas to be in the ISQPR from low pressure[3)]. We conjectured that the inert gas injected onto the burning surface accelerated the heat convection involving the surrounding hot gas. Thus, the propellant would have been difficult to quench in the ISQPR despite the pressurization by inert gas injection. The actual burning rate was rather increased and the average chamber pressure shifted from 3 MPa to 5.5 MPa.

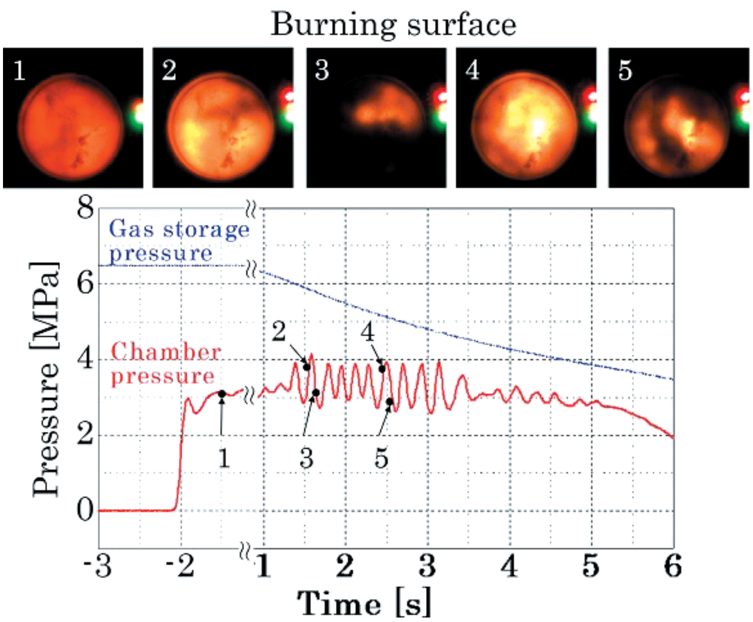

Figure 4 Pressure history and corresponding burning aspects with an inert gas injected into the nozzle throat.

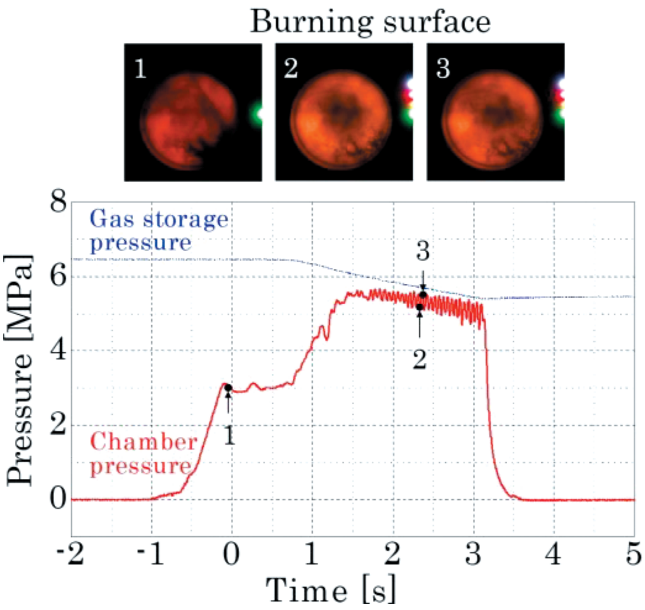

Figure 5 Pressure history and corresponding burning aspects with inert gas injected onto the burning surface.

4.2 Effects of the timing of water spray on combustion extinction

Inert gas injection in two directions made the chamber pressure oscillate and the surface luminance flicker accordingly. Inert gas injection in two directions also held the average pressure sufficiently high in the ISQPR. Figure 6 shows the pressure and temperature history of Experiment B. The combustion was not interrupted. Figure 7 shows a magnified image of the waveform shown in Figure 6 as well as aspects of the burning surface. The water was sprayed at a local maximum of pressure oscillation. Around the local maximum of pressure oscillation, the flame area was fully developed. After water spraying, the pressure decreased to 3.3 MPa and then recovered. The chamber temperature also decreased from 1,300 K to 700 K and then increased. In Figure 7, picture 3 shows the darkest burning surface after the water spray. After the point 3, the burning surface gradually brightened. Picture 4 shows the recovering burning surface. There was a delay between the start of recovering the burning surface and the start of recovering the chamber pressure. We conjectured that the delay was caused by the chamber stay time of cooled combustion gas.

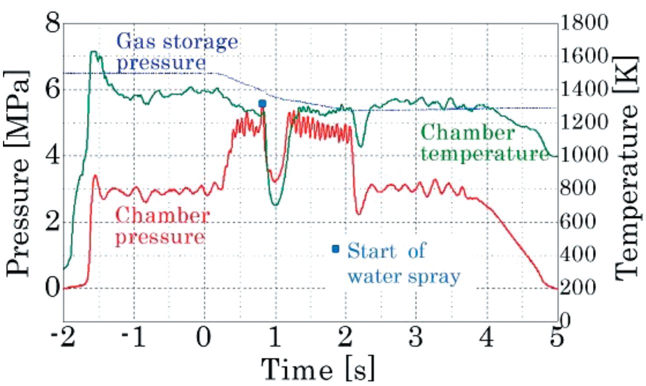

Figure 6 Pressure and temperature history with water sprayed at a local maximum of pressure oscillation.

Moreover, in Experiment B, water was sprayed at a local minimum of pressure oscillation. Around the local minimum of pressure oscillation, the flame area decreased to a small area. The combustion was not interrupted. Experiment B was conducted 17 times while changing the timing of water spraying during the controlled chamber pressure oscillation and flame propagation aspect transition. However, the combustion interruption was never completed. The chamber pressure at the instance of water spraying ranged from 4.1 MPa to 5.6 MPa. These results revealed that, when the chamber pressure decreased below the lower limit of the ISQPR, the small flame reappeared and propagated over the entire surface, reestablishing high pressure.

We conducted another experiment with water spraying in which we pressurized the combustion chamber at higher pressure than in the above experiment by inert gas injection from stored high-pressure gas. We attempted to spray water into the chamber pressure near the higher limit of the ISQPR. The initial pressure of the inert gas was changed from 6.5 MPa to 8 MPa. The result is shown in Figure 8. The combustion was interrupted after water spraying. Figure 9 shows the magnified graph as well as aspects of the burning surface. Inert gas injection made the chamber pressure oscillate and the flame area flicker on the burning surface at higher pressure than the previous pressure. The chamber pressure was 6.4 MPa when the water was sprayed. The flame was extinguished in the ISQPR. The high-pressure experiments were conducted four times, and complete interruption was achieved twice. The results were stochastic because the self-quenching or reignition phenomenon itself bears a probabilistic aspect. We conjectured that the complete quenching of flame required some duration and that keeping the chamber pressure within the ISQPR for a sufficient time was crucial. From a comparison of the

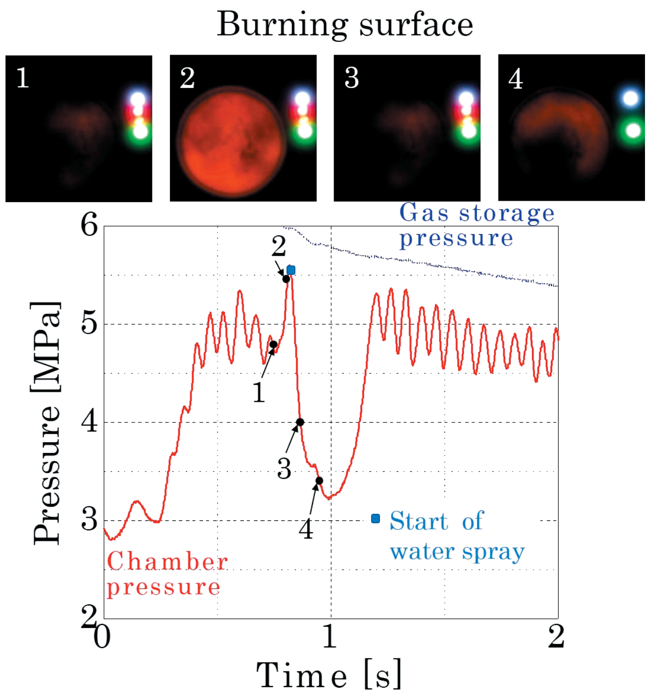

Figure 7 Enlarged image of the waveform shown in Figure 6 and corresponding aspects of the burning surface.

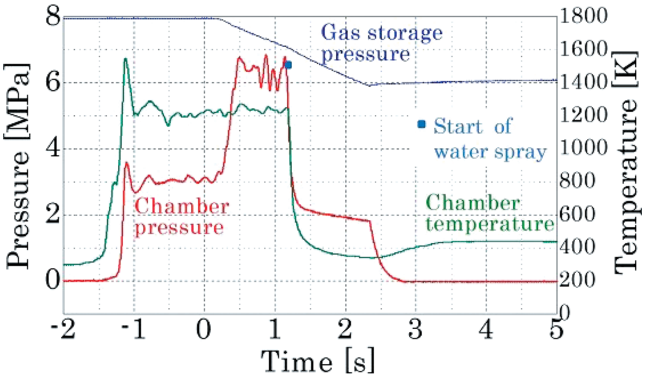

Figure 8 Pressure and temperature history with water sprayed in the high-pressure chamber.

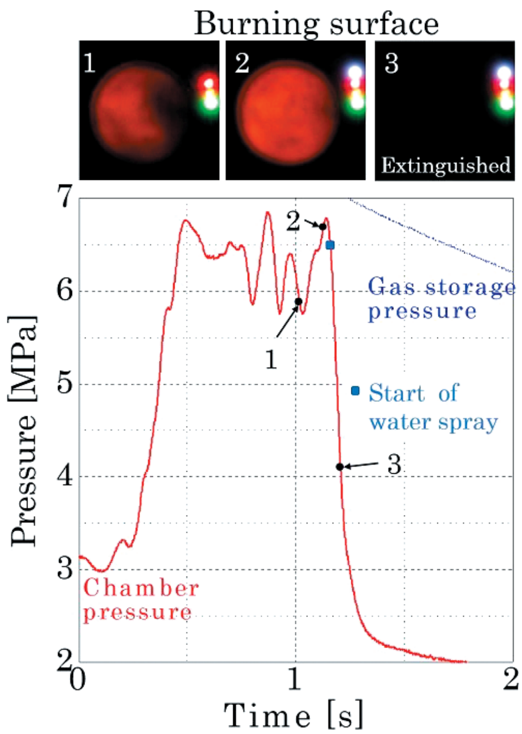

Figure 9 Enlarged image of the waveform shown in Figure 8 and corresponding aspects of the burning surface.

results obtained for different initial gas storage pressures, starting the water spray at a high average pressure level a priority was clarified to be important for combustion interruption. Setting the spray timing of water at some instance during the chamber pressure oscillation and the fluctuation of the flame propagation area were found to be less important.

5. Conclusions

We clarified the effect of inert gas injection on the chamber pressure and the flame propagation. The chamber pressure and the flame propagation were controlled by adjusting the direction of inert gas injection. When inert gas was injected toward the throat, the chamber pressure was not increased in an average manner, but rather oscillated with high amplitude, and the flame repeatedly propagated and shrank over the entire burning surface. The burning surface flickered in synchronization with the chamber pressure oscillation at low frequency. When the inert gas was injected toward the burning surface, the average chamber pressure was increased sufficiently into the ISQPR, and the flame flickered rapidly in discrete local areas.

Moreover, we clarified the effect of pressurization by inert gas on combustion interruption with a water spray. For combustion interruption with the water spray, it was of primary importance that the chamber pressure was held adequately in the ISQPR during the decrease in pressure. It was not essential for the entire quenching that the timing of water spraying was set at some instance during the chamber pressure oscillation or the flame-propagation area fluctuation.

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