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One-dimensional Modeling of Ignition Timing for Hypergolic Bipropellant Thrusters

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Abstract

1D modeling were developed to predict an ignition time in a vacuum of space propulsion systems. Bipropellant liquid propulsion system with hypergolic propellant have been generally used for attitude control and orbit maneuvering of spacecrafts and satellites. In a pulse-firing mode of the space propulsion system, the prediction of the ignition time is very important to guarantee a minimum impulse bit. In this paper, ignition experiments were conducted in a vacuum to clarify the ignition process. An ignition model for 1D simulation were proposed based on the ignition test results. The simulation reproduced the ignition time for the thrust level changes.

1. Introduction

Bipropellant liquid propulsion systems based on hydrazine and its derivatives are widely used in many satellites and spacecraft and offer the advantage of hypergolic ignition. Hypergolic ignition starts when the liquid fuel and oxidizer come into contact, resulting in spontaneous ignition in the gas phase. Although recent research has revealed this phenomenon [1], the ignition mechanism is not fully understood. In the previous work [2], we observed ignition phenomena in a thruster during pulsed combustion under ambient pressure through visualization tests. The ignition delay was due mostly to the time required to fill a thruster manifold. The ignition delay after the second pulse, when the manifold was expected to be full, was about 1 ms. In other words, the ignition delay due to chemical reaction should be less than 1 ms if the fuel and oxidizer are in liquid-to-liquid contact. A droplet ignition test showed that the liquid-liquid reaction took 20 μs [1], and the subsequent gas phase ignition was also around 1 ms [3-5]. All these tests and simulations were conducted under atmospheric pressure, and there is little in the literature about vacuum conditions experienced in the space environment. The ignition delay of the chemical reaction can be as short as 1 ms, and the ignition delay of a propulsion system can be obtained from the time it takes for the liquid to fill the thruster manifolds. Thus, a 1D system simulation should be able to predict the ignition delay for as a propulsion system.

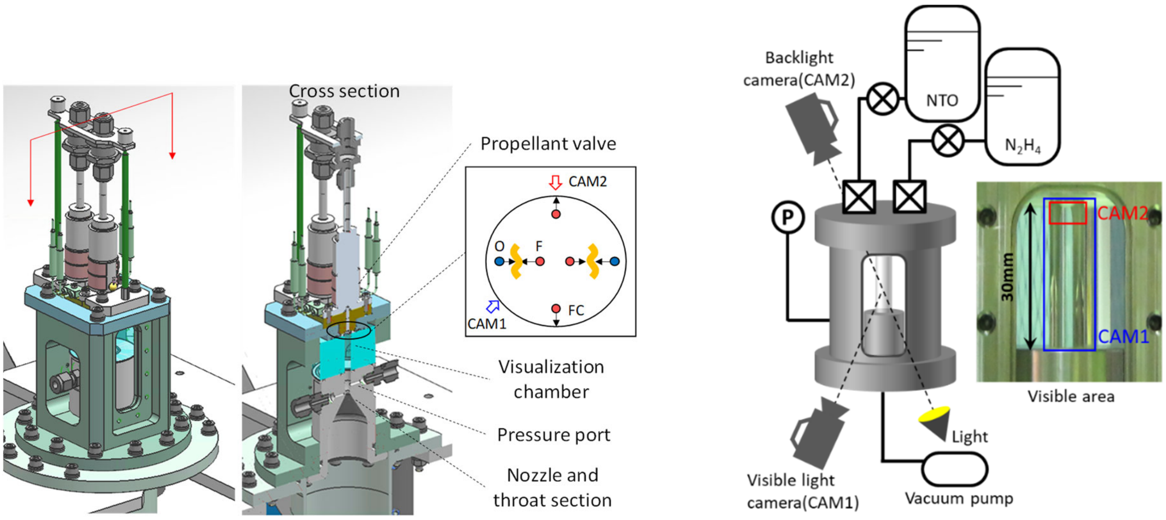
This paper presents a method for predicting the thruster ignition delay time of a liquid propulsion system in vacuum by 1D system simulation. This enables us to determine whether the thruster ignites within the valve opening time and to predict the minimum impulse bit. Ignition experiments were conducted in a vacuum to model and clarify the ignition process. The paper then compares the test and simulation results.

2. Experimental Apparatus and Simulation Setups

2.1 Ignition Test with Visualization Chamber

Visualized ignition tests were conducted to provide information on the hypergolic ignition inside a thruster with hydrazine (N2H4) as the fuel and NTO (dinitrogen tetroxide N_2O_4 with a few percent impurities) as the oxidizer. Figure 1 shows the visualization chamber of the experimental apparatus and a schematic diagram. The chamber consists of

two propellant valves, an injector head, a visualization section, a nozzle, a throat section, and a pressure measurement port. The injector head has two pairs of injection holes for the fuel (F) and oxidizer (O) and two film cooling (FC) holes for the fuel. Turning the propellant valve on and off pulses the fuel and oxidizer injection, resulting in a short combustion time. The nozzle throat was connected to a vacuum pump downstream to reproduce the ignition and extinguishing of flames in space. The pressure in the visualization chamber was measured at 2000 Hz by a pressure sensor (KYOWA PHL-B-3MP) through the pressure measurement port. Two high-speed cameras were used: CAM1 (Photron FASTCAM NOVA S16), which captured a full view of the combustor through visible light and CAM2 (Photron FASTCAM SA-Z), which captured images near the injector through backlighting from a high-intensity light source. The images were taken at 25,000 fps and 40,000 fps, respectively.
The experimental conditions are 12 and 18 N for the same valve opening timing, and 12, 16, 18, and 22 N for the oxidizer valve lead opening (30 ms). The chamber pressure before injection start was set to less than 0.001 MPaG. The mixing ratio (MR) (i.e., mass flow rate QO/QF) was as set to MR = 0.8. The duration time is 20 ms (the same timing for opening the valve) or 80 ms (the oxidizer valve opening leads the fuel valve for 30 ms).



(a) Visualization chamber and injector holes. (b) Schematic diagram of experimental apparatus

Figure 1: Experimental setups.

2.2 1D Dynamic Response Simulation for Liquid Propulsion Systems

A Modelica [5] based platforem, SimulationX [6], was modeled for a 1D dynamic response simulation of a liquid propulsion system. ProMPT [7] was employed to develop a tool to predict unsteady performance for predicting the thruster performance of a bipropellant impinging-type combustor directly from the injection parameters (e.g., the injection hole diameter, number of holes, propellant flow rate, and MR).
Figure 2a is the schematic diagram of a simplified liquid propulsion system. Although an actual liquid propulsion system has a complex piping system with multiple thrusters and branch pipes for liquid waste in ground tests, only the major components are shown here for illustration. This diagram shows the tanks, valves, injectors, and chambers. Figure 2b is the model diagram of this system using SimulationX. The fuel and oxidizer pipes are modeled independently, and ProMPT uses the mass flow rate of SimulationX results to determine the combustion pressure as boundary conditions. Figure 2c shows the one-dimensional model of the pressure measurement port. Since the port is connected to the combustion chamber in the experiment, the model needs only to connect the port directly to the combustion chamber. However, as Figure 2b shows, separate lines upstream of the combustion chamber lead from the fuel and oxidizer tanks to valves. The combustion chamber is common to both but is not modeled as a volume. In addition, the liquids were fuel and oxidizer, and combustion gases were not modeled in the 1D dynamic response simulation. The pressure measurement port was modeled separately from the fuel and oxidizer piping. As shown in Fig. 2b, the pressure obtained by ProMPT was applied to the combustion chamber volume as a boundary condition to simulate the pressure at the pressure gauge.

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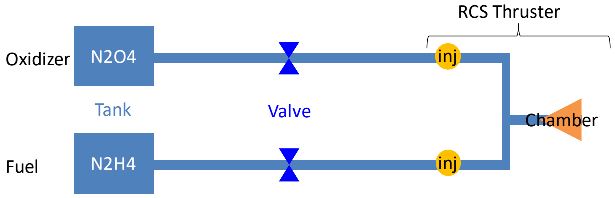
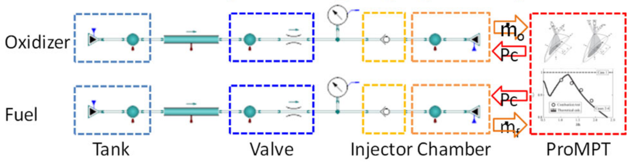
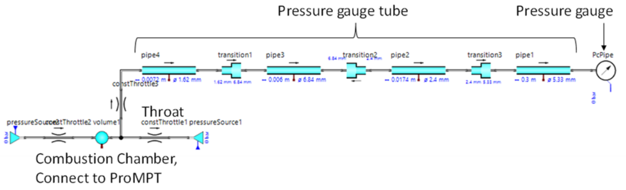


(a) Schematic diagram of liquid propulsion system



(b) Model diagram of SimulationX



(c) 1D model of pressure gauge tube.

Figure 2: Schematic diagram and model of dynamic response simulation.

3. Results and Discussions of Visualized Ignition Test

3.1 Ignition and Non-Ignition Cases in Simultaneous Valve Opening Mode

Figure 3 shows the pressure histories upstream from the valve (PIF: fuel, PIO: oxidizer) and the chamber pressure histories through the measurement port (Pc). The thrust conditions were 10 and 18 N. The signals to open the fuel and oxidizer valves were sent at t= 0 s. The pressure upstream from valves dropped at t= 0.004 s, which indicated that the valves had opened and the liquid was moving through the piping. The pressure at the measurement port increased gradually from t= 0.006 s. For the 18 N test, the pressure at the port began to increase rapidly at t= 0.0115 s. This represents hypergolic ignition. However, the fast pressure increase did not appear for 10 N. The pressure histories at 10 and 18 N were almost identical until t= 0.0115 s. Note that this is not the combustion pressure in the thruster, but rather at the measurement port, which is larger than the combustion chamber. The pressure timing at the port was delayed from the phenomenon in the thruster. The pressure measurement port must be modeled to compare the simulation results with the experimental data.

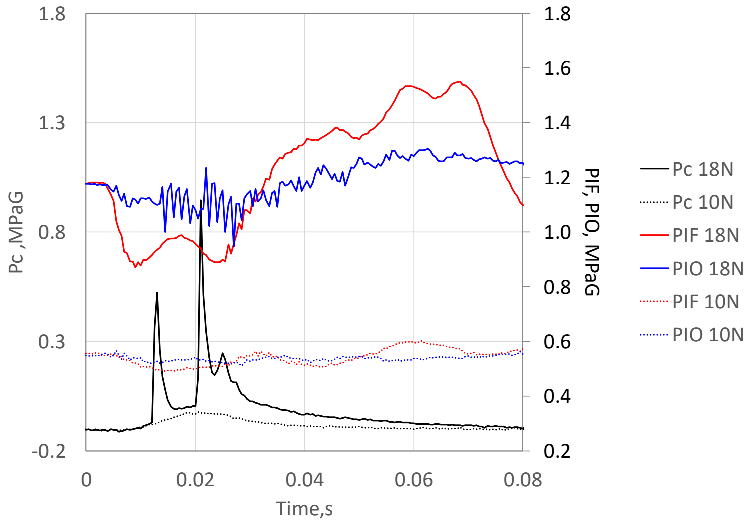


Figure 3: Pressure histories upstream of valve and chamber pressure through pressure measurement port

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Figure 4 shows the high-speed images captured by CAM1 for 10 N. At t= 0.006 s, gaseous oxidizer and fuel droplets were observed. From these features, we expect that the chamber pressure were the saturated vapor pressures of oxidizer and fuel, 1.4 kPa and 95 kPa, respectively. At t= 0.010 s, the fuel for FC appeared to be boiling. This was higher than at the saturated vapor pressure of fuel as shown in Fig. 3. Thus, the boiling indicated the liquid-liquid reaction of liquid fuel and droplet oxidizer on the chamber wall. This reaction gradually increased the chamber pressure, as shown in Fig. 3. Subsequently, FC boiling was still observed at t= 0.012 and 0.020 s. Figure 5 shows the high-speed images captured by CAM1 for 18 N. At t= 0.006 and 0.010 s, the physical phenomena that appeared were almost the same as in Fig. 4. Ignition occurred at t= 0.012 s. After the close signals were generated, the second ignition occurred at t= 0.020 s.

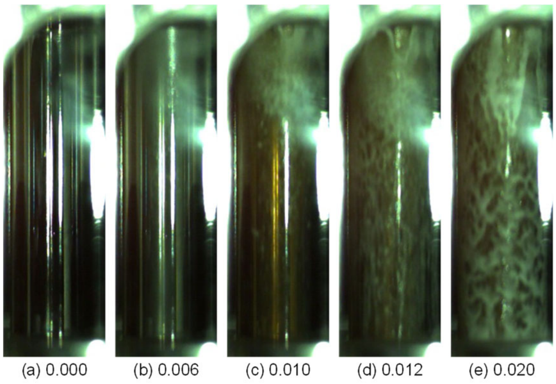
(a) 0.000 (b) 0.006 (c) 0.010 (d) 0.012 (e) 0.020

Figure 4: High-speed camera images of 10 N.

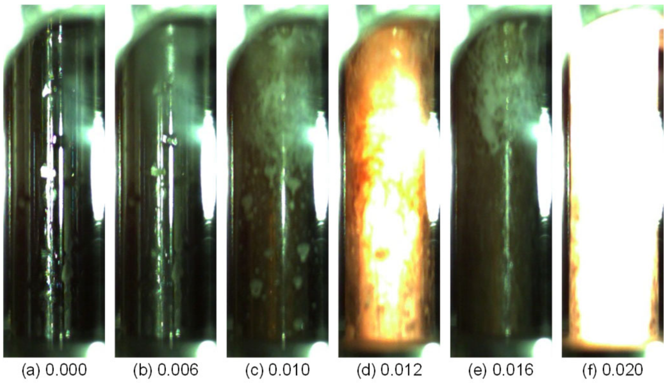
(a) 0.000 (b) 0.006 (c) 0.010 (d) 0.012 (e) 0.016 (f) 0.020

Figure 5: High-speed camera images of 18 N.

Figure 6 shows the pressure histories at the measurement port for thrusts of 22, 18, 16 and 12 N. The oxidizer valve opened at t= 0 s. The port pressure gradually increased from t= 0.008 s in all cases. The choke condition and the evaporation rate of the oxidizer determine this pressure. The fuel valve opened at t= 0.03 s. The pressure at the measurement port increased again from t= 0.034 s. Figures 3-5 show the pressure increase due to the reaction between fuel and oxidizer. Individual ignitions were then confirmed in the order of thrust.

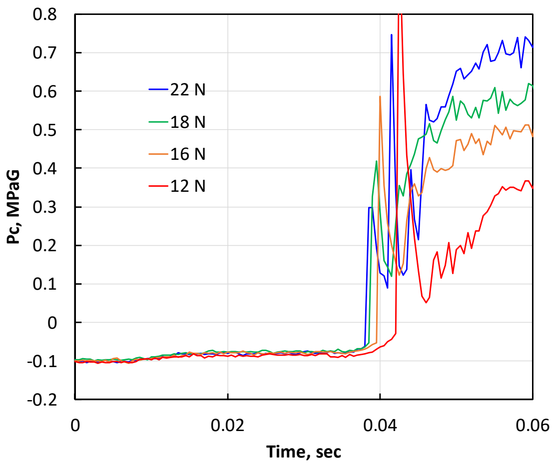

Figure: 6 Comparison of ignition delay with various thrusts

The ignition process was reconsidered based on Figs. 3-6. Figure 7 shows the schematic diagrams of the ignition process. The chamber pressure in the first stage is a vacuum because the thruster will be used in space. After the valves opened, the fuel and oxidizer were introduced into the manifolds, as shown in Fig. 7a. The chamber pressure increased because the fuel and oxidizer reached the combustion chamber (Fig. 7b). The chamber pressure rose between the fuel and the oxidizer saturated pressures. At this point, the oxidizer jet became gaseous. Figure 7c shows that the oxidizer manifold pressure rose to the saturated pressure or a little higher. Cavitation occurred in the injector, and the oxidizer jet became a mixture of gas and liquid droplets. The droplets then reacted with the liquid fuel of the FC. Next, the chamber pressure rose and the liquid oxidizer reached the combustion chamber, as shown in Fig. 7d. The oxidizer and fuel demonstrated the liquid-liquid reaction and ignited within 1 ms. Therefore, the ignition delay of the bipropellant liquid propulsion system in space is mainly initial three steps in Figs. 7a-7c.

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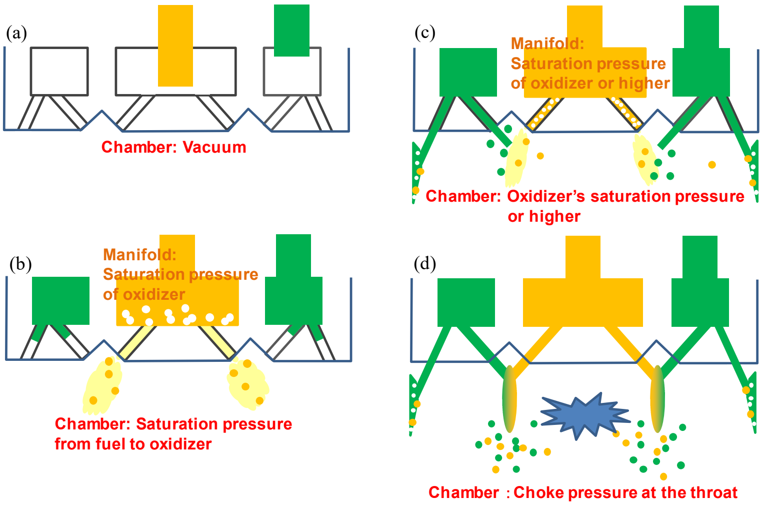


Figure 7: Schematic diagrams of the ignition process from (a) to (d)

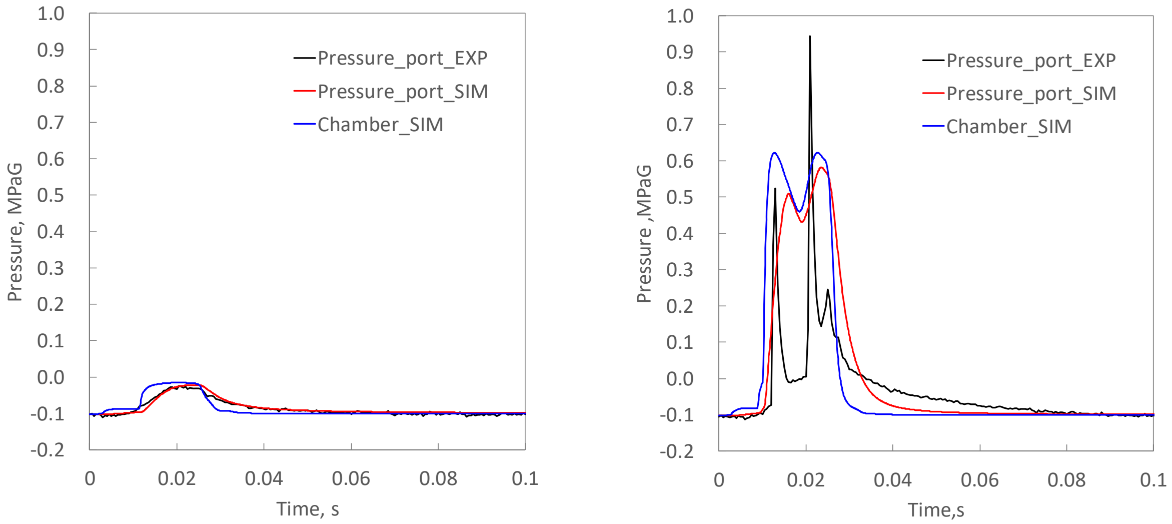
4. Simulations

4.1 Modeling of Hypergolic Ignition

The 1D simulation model was update based on the ignition process in Fig. 7. In order to take into account for filling time into the manifold, the volumes of the manifolds were modelled in the simulation. The propellant component was in the mixture of liquid and gas state and exited the throat as shown in Fig. 4. Thus, we also modeled the evaporation of a part of the oxidizer in the combustion chamber. The oxidizer injection phase was determined from the cavitation number for the oxidizer's cavitation. If the simulated cavitation number exceeded a certain value, the oxidizer was determined to be liquid and was modeled to ignite within 1ms.

4.2 Results and Discussion for Simultaneous Injection

Figure 8 shows the pressure histories for 10 N and 18 N thrust. It includes the measured and simulated port pressures, and the simulated chamber pressure. The simulation did not model the explosion in the combustion chamber, so the paper discusses only the pressure histories up the ignition time. The simulation results recreated the pre-ignition pressure histories and the ignition criteria. The chamber pressure was slightly higher than at the simulated measurement port. In future studies, we plan to use the flash-mounted sensor to monitor the chamber pressure.



(a) 10N (b) 18N

Figure 8: Comparison of pressure histories between experimental data and simulation results.

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4.3 Results and Discussion for Oxidizer Lead Injection

Figure 9 shows the comparison of ignition time between the experimental data and the simulation results for thrusts of 22, 18, 16, and 12 N. The oxidizer valve opening leads the fuel valve by 30 ms in these cases. The error of the simulated ignition time is within 1 ms relative to the experimental one. The simulation tool has been validated for the thrust level changes.

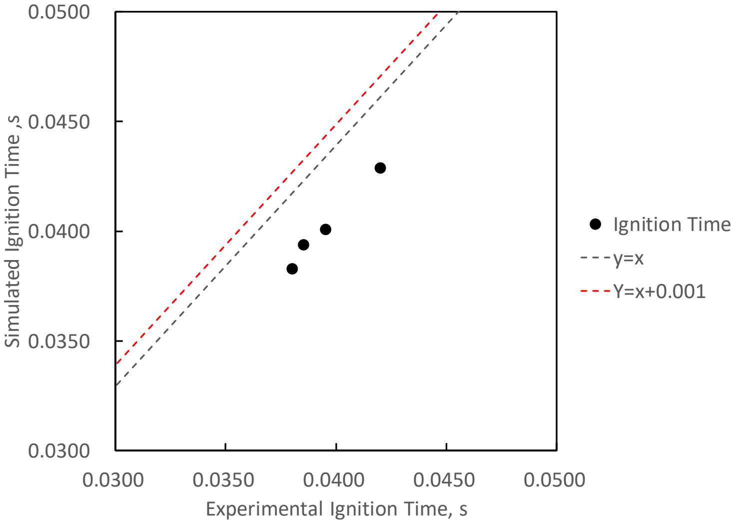

Figure 9: Experimental and simulated ignition time.

5. Conclusions

The visualized ignition tests and 1D system simulation were conducted to model the ignition delay time of hypergolic bipropellant propulsion systems. At 18 and 10 N thrust tests with 20 ms duration time, ignition and non-ignition test results were obtained. The pressure histories at the measurement port connected to the combustion chamber before the ignition were the same in both cases. Because the propulsion system starts from the vacuum in the thruster, the decompressed boiling occurred in the combustion chamber at the beginning stage. The gaseous injection was observed in the high-speed images. After the reaction of the film cooling fuel and the oxidizer droplet, the ignition occurred and showed the pressure peak. Based on these physical phenomena, the ignition process proposed. The decompressed boiling and the cavitaion in the injector were the important features. Especially, the cavitation in the injector was the criteria to determine whether ignition was possible or not. The 1D simulation recreated the ignition time using this criteria. The error of the simulated ignition time was within 1 ms relative to the experimental one for thrusts of 22, 18, 16, and 12 N.

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