Semi-Hypergolic Kerosene/Hydrogen Peroxide Fuel System and Its Auto-Ignition Injector Design

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Semi-Hypergolic Kerosene/Hydrogen Peroxide Fuel System and Its Auto-Ignition Injector Design

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Combination of kerosene and hydrogen peroxide is a promising bipropellant due to its low cost, low toxicity, long storability, and high propulsive performance. This research formulates a kerosene based fuel which shows semi-hypergolic characteristics when in contact with hydrogen peroxide. Choosing a proper promoting medium, the formulated fuel (W2) dissolves ~8wt% of MAT in the solution with ~21wt% of kerosene, which makes the heating value of W2 closes to 32.5kJ/g. W2 and hydrogen peroxide present an ignition delay time of 21ms in droplet contact test. Since the delay time is still long comparing to conventional hypergolic propellant systems, a premixed type bipropellant injector design, namely, liquid-cyclonic injector unit has been preliminarily designed to obtain auto-ignition capability. In the injector unit, liquid fuel and oxidizer are tangentially injected into a small cylindrical chamber simultaneously to mix, and the formed hollow center space holds the vaporized propellants due to the heat release from the catalytic reaction in liquid phase. Ignition occurs when the gas-phase temperature reaches its auto ignition point. In hot-fire experiments, the designed injector shows a wide range in flow rate and O/F for stable auto-ignition. The shortest ignition delay of the injector unit is 38ms, however non-reproducible. Further study of the control factors for stable ignition delay is required.

Nomenclature

ΔH	=	heating value
Δt	=	ignition delay
O/F	=	oxidizer to fuel ratio
MAT	=	manganese acetate tetrahydrate
RGHP	=	rocket grade hydrogen peroxide

I. Introduction

Tradictional hypergolic propellants such as the combination nitrogen tetroxide(NTO) and monomethyl hydrazine (MMH) were widely adopted in the space shuttle orbital maneuvering systems and the reaction control systems (RCS) for their storable, high performance, and most import hypergolic characteristics. Yet, hydrazine based compounds are identified to be toxic, and NTO has a high vapor pressure and is very corrosive to both rocket hardware and the human body.[1] Not only for the environmental issue but also storing these propellants for long duration space missions poses a major safety hazard. For these reasons, some green propellants have been developed in recent years. High concentration hydrogen peroxide, which decomposes into hot oxygen and steam through catalytic reaction is regarded as monopropellant or the oxidizer of bipropellant systems. In combination with kerosene, the bipropellant system has high heat of combustion and produces CO_2 and H_2O, is considered to be an nontoxic propellant system. In the previous research, transition metal salts has dissolved in energetic liquid to create hypergolic fuels. These dissolved salts decompose rocket grade hydrogen peroxide (RGHP) on contact, producing heated oxygen and steam which ignite the remainder of the fuel. Manganese (Mn^{2+}) had previously displayed very good decomposition rate of hydrogen peroxide in mixture of methanol and manganese acetate tetrahydrate (MAT), namely block 0. Recently, two classes of hypergolic fuel are under developing based on the behavior of the additives. Catalytic hypergolic propellants utilize dissolved transition metal salt as catalyst and dissociate hydrogen peroxide in contact, while reactive hypergolic propellants utilize dissolved light metal compound which is oxidized by hydrogen peroxide in the ignition process.[2-7] Although the ignition delay of these catalytic hypergolic propellants are approximately dozens milliseconds which are substantially greater than the several milliseconds of NTO/MMH[8], the catalytic hypergolic propellants are still more safe, easy to storage, clean, and with an acceptable ignition delay time. Kerosene based fuels like RP series and JP series are commonly used in rocket and airplane. The theoretical Isp of RP-1 and Block 0 with hydrogen peroxide are calculated by NASA CEA code (Fig. 1), which of RP-1 is obviously higher than Block 0. The development of high propulsion performance kerosene based fuel/RGHP is important for the improvement of nontoxic propellants.

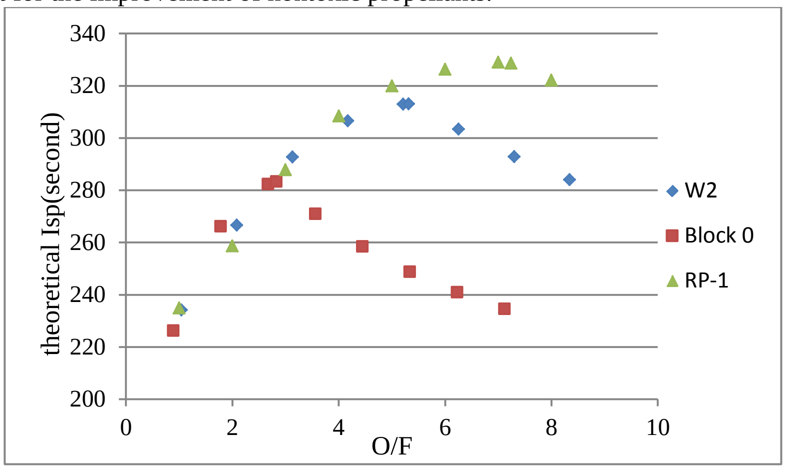


Figure 1. Theoretical Isp of propellants (chamber pressure=150psi and nozzle expansion ratio=100)

II. Experimental Approach

To further the use of these hypergolic propellants, the preparation of hypergolic propellant which involved high heating value kerosene based fuel and grade hydrogen peroxide (RGHP) and the design of a matching injector have been investigated in this research. Droplet contact tests between the formulated kerosene base fuel and RGHP were conducted to preliminarily exam the ignition delay time of each formulated fuel. Combine with the consideration of heating value and the storability of the fuel, an specific formulated fuel was chosen and a “cyclonic” injector was designed to meet the requirement of the auto-ignition propellant system.

III. Preparation of Propellant

Pure kerosene would not auto-ignite with RGHP and the transition metal compound like Mn^{2+}, Cu^{2+}, Co^{2+} which have been indicated good decomposition rate with RGHP are not soluble in kerosene. Because the polar metal salts are only dissolved in polar solvent, methanol has be chosen as the first stage medium to solve metal salts. In order to mix the methanol solution and kerosene, some surfactant have been tested. Referring to the hydrophilic-lipophilic balance(HLB)[9], the Fatty alcohols are chosen as the second stage medium to prepare kerosene based fuel. Several series candidate fuels were screened by conducting storage capacity tests and the droplet contact tests.

Generally, hypergolic reaction can exam through a droplet contact test. The droplet contact test stand is consisted of the steel pool, the acrylic cover, and dropper (Fig. 2). The hypergolic phenomena were recorded by Phantom v711 high speed camera with a Sigma 180mm lens recording at 5000 fps.

Figure 3 shows methanol/MAT solutions and the formulated fuel ignition process in droplet contact test. When the oxidizer droplet contacts on fuel(Fig. 3a), the mixing propellant discomposes to O_2 and hot stream, and releases energy to vaporize fuel(Fig. 3b). Then the vaporized fuel ignites with O_2 after a period of time(Fig. 3c). The definition of ignition delay time in this study is from droplet contacts to the first spark occurs. In the tests, the oxidizer(RGHP) always dropped on the fuel with the O/F(oxidizer to fuel ratio) approximately 0.8(oxidizer/fuel: 0.0385g/0.0465g). Selected candidate of formulated fuels and their corresponding delay time determined by the high speed video are listed in Table 1. The ignition delay results of methanol/MAT solution are shown in Figure 4(blue points). The catalysts should be dissolved enough to assure rapid hypergolic ignition. But the catalytic fuels are generally the result of a trade-off between ignition delay and propulsion performance.

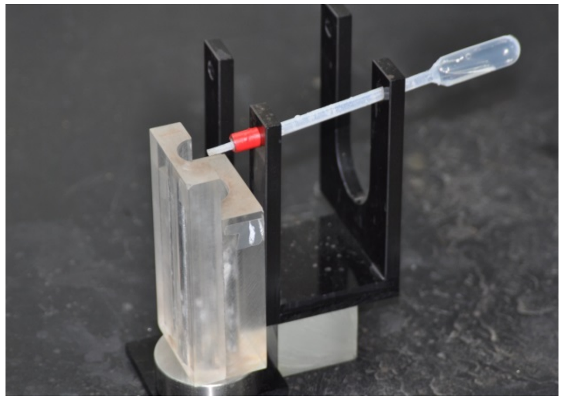
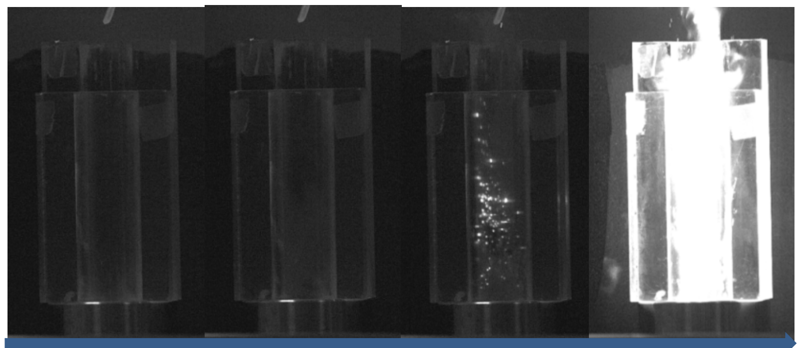


Figure 2. Apparatus of droplet contact test



a)contact,0 ms b)10 ms c)21 ms d)30 ms

Figure 3. Typical droplet contact test sequence of W2/H_2O_2

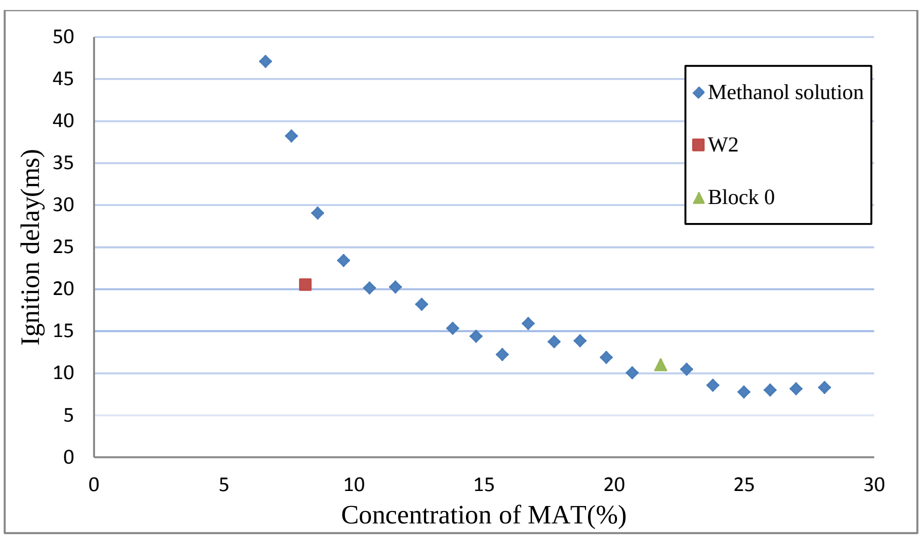


Figure 4. Droplet contact test sequence of W2/H_2O_2

Finally, the high heating value (ΔH=-32.5kJ/g) nontoxic kerosene based fuel is developed, namely W2, which is composed of kerosene (~21%wt), dissolved transition metal salts (~8.1%wt), the polar organic solvent, and a dispersion medium to homogenize the solution and make miscible with RGHP. The combination of W2 and RGHP were developed as semi-hypergolic (Δt=20ms, red point in figure 3) bipropellants in this study. The results show the delay of W2 is greater than Block 0 but shorter than which of the same concentration of methanol/MAT solution. The low temperature storability and its droplet contact test of W2 are also examine and the results (Fig. 4) shown that W2 could be stored from -10°C to room temperature without separation and the ignition delay longer with lower temperature.

After all the droplet contact tests, W2 is chosen to be the target fuel for the following design of the matching injector and adopted in hot-fire experiments to perform the hypergolic behavior.

Table 2. Drop test results

Methanol/MAT solution	
Concentration of MAT(%)	Ignition delay, Δt(ms)
28.1	8.3
27	8.2
26	8.0
25	7.8
23.8	8.6
22.8	10.5
20.7	10.1
19.7	11.9
18.7	13.9
17.7	13.7
16.7	15.9
15.7	12.2
14.7	14.4
13.8	15.4
12.6	18.2
11.6	20.3
10.6	20.2
9.6	23.4
8.6	29.1
7.6	38.2
6.6	47.1

W2	
Concentration of MAT(%)	Ignition delay(ms)
8.14	20.5
Block 0	
Concentration of MAT(%)	Ignition delay(ms)
22	11.0

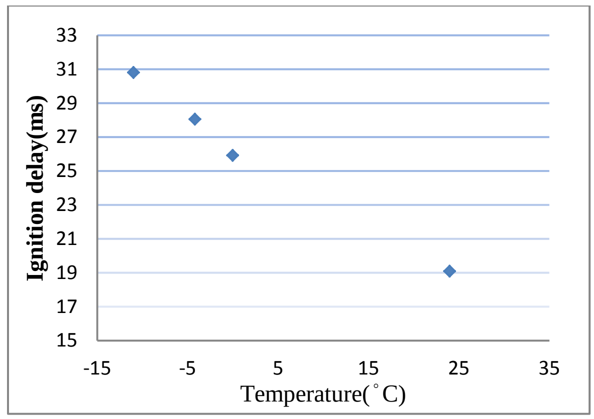


Figure 4. Results of droplet contact test under various temperature

IV. Hot-Fire Experiments

Since impinging type injectors are widely adopted in rocket propulsion, the preliminary open hot-fire experiments of W2/RGHP with 0.4mm orifice diameter doublet impingement injector is conducted(Fig. 5). After impinging, decomposed gases are observed at 13cm below impinging point but not auto-ignite because the high speed stream after impinging take greatly heat away and cause energy density is not enough to ignite.

A. Design of Liquid-Cyclonic Injector

Since the formulated semi-hypergolic propellants require a finite contact time to react, a liquid-cyclonic injector unit had been designed to meet the requirement to auto-ignite W2/RGHP. A drawing of a preliminary designed injector is shown in Fig 6a. As is shown in Fig. 6b, liquid fuel and oxidizer are tangentially injected into the small cylindrical chamber from top-mounted orifices. High-speed liquid cyclone can be achieved in the chamber with hollow(without liquid) center space. The period of liquid propellants staying and mixing in the chamber provides the required time for liquid catalytic reaction to produce enough heat to gasify liquid propellants, and the formed hollow center space which is with negative pressure holds the vaporized propellant to perform gas-phase oxidation reactions to its auto ignition temperature.

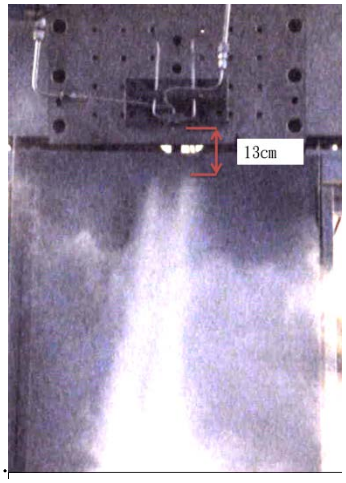


Figure 5. Open hot-fire experiments of W2/RGHP with 0.4mm orifice diameter doublet impingement injector

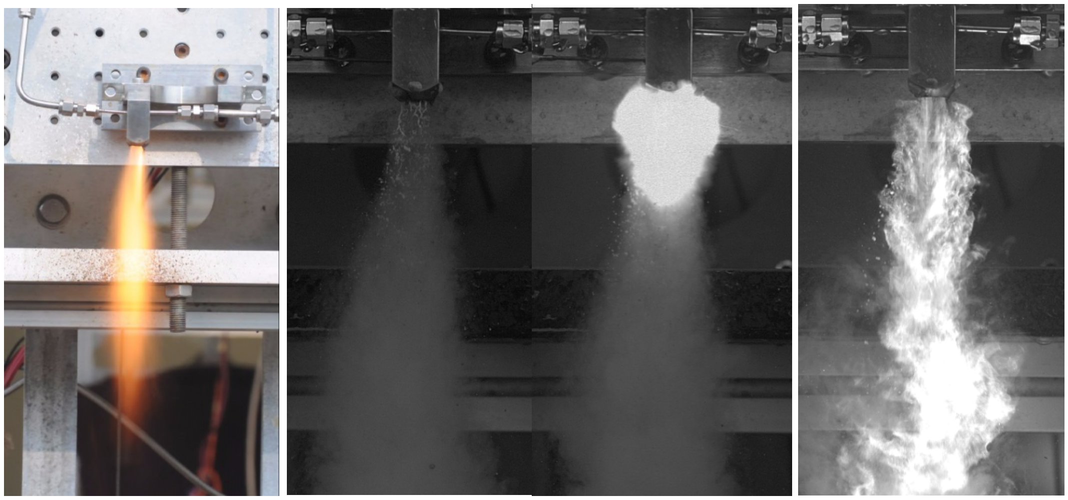
a)Solidworks drawing a)cold flow test module a)hot fire test module

Figure 6. The liquid cyclonic injector

B. Results and Discussion

In early validation of the design by hot-fire tests recording by high-speed camera, it is shown that the liquid cyclonic injector could provide an acceptable ignition delay time with sustained steady flame as shown in Fig. 7.

By controlling the total mass flow rate from 4g/s to 16.5g/s and O/F from 1.5 to 9, the hot-fire experiments are conducted to exam the steady operation limits and the ignition delay time and of the injector and the results shown in Fig. 8. There are approximately three conditions make the ignition or combustion phenomenon unsteady. When the total mass flow rate is greater than 14g/s and O/F is higher than 7(red area in Fig. 8), intermittent combustion occurs because of the overshoot pressure during the ignition. When the total mass flow rate approximately 8g/s and O/F higher than 6(blue area in Fig. 8), the unstable flame occurs because the pressure drop of fuel line is too small to supply steady. And the incomplete combustion occurs becuause of very low O/F when O/F lower than 1(green area in Fig. 8). In addition to these operation limits, the fast ignition delay time, 38ms of the propellant and matching injector is observed with stable auto-ignition.



a) average image b) t=15ms c) t=47ms c) t=50ms

Figure 7. The hot-fire experiment of liquid cyclonic injector unit

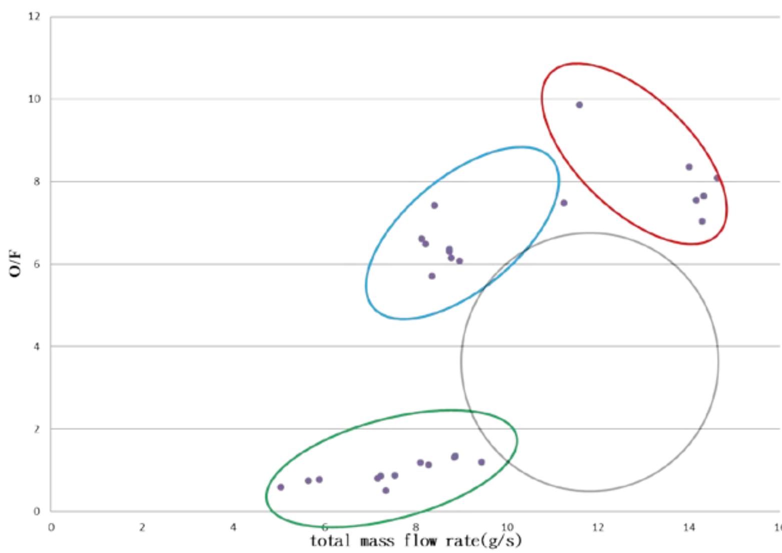


Figure 8. The operation limits of the W2/RGHP with corresponding injector

In practical, the combustor design is affected by the flame length and angle of single injector unit. In this study, the definition of flame length is the length from outlet of injector to the violent reaction position where determined by the highest intensity of the average image during hot-fire experiments (Fig. 9). As the results shown (Fig. 10), the flame length are about shorter with fixed flow rate and higher O/F until about 6 which is corresponding to stoichiometric. The injector is suitable to be the igniter or to arrang injector plate because its flame is steady sustained and rapid reaction.

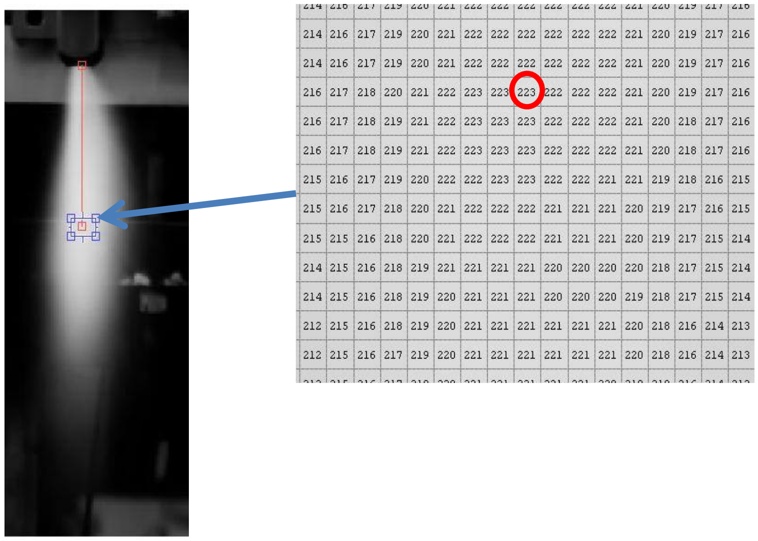


Figure 9. The determination of flame length

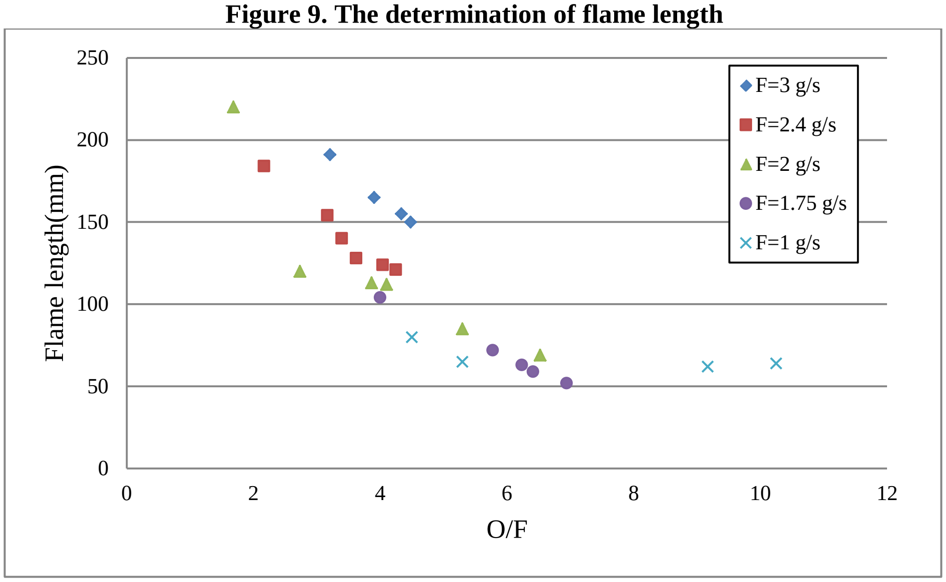


Figure 10. Flame length vs O/F at various flow rate of fuel

Conclusion

The preparation of hypergolic propellant which involved high heating value kerosene based fuel/RGHP and the design of a matching injector have been investigated in this study. The high heating value (ΔH=-32.5kJ/g) nontoxic kerosene based fuel (W2) is developed which is composed by kerosene, dissolved transition metal salts, the polar organic solvent, and a dispersion medium to homogenize the solution and make miscible with RGHP. The combination of W2/RGHP were developed as semi-hypergolic (Δt=21ms) bipropellants in this study. Since the formulated semi-hypergolic propellants require a finite contact time to react, a light and simple liquid-cyclonic injector unit had been designed to meet the requirement to auto-ignite W2/RGHP with wide operation limits. In the injector unit, liquid fuel and oxidizer are tangentially injected into a small cylindrical chamber instantaneously to mix, and the formed hollow center space holds the vaporized propellants due to the heat release from the catalytic reaction in liquid phase. Ignition occurs when the gas-phase temperature reaches its auto ignition point. In hot-fire experiments, the designed injector shows a wide range in flow rate and O/F for stable auto-ignition. The shortest ignition delay of the injector unit is 38ms, however non-reproducible. Further study of the control factors for stable ignition delay is required.

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