Hyperfugility and ignition delay study of pure and energized ethanol gel fuel with hydrogen peroxide

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Article info

Article history:
Received 9 September 2016
Revised 17 November 2016
Accepted 17 November 2016

Keywords:
Ethanol
Gel
Propellant
Hypercitic
Ignition delay
Viscosity

Abstract

An experimental study of hypergugility and ignition delay of pure and energized gelled ethanol with hydrogen peroxide was carried out. Experimental drop test results were obtained and discussed by using Photron high speed camera imaging. This study represented a sufficient repeatability of ignition delay for hyperguglic gel bipropellant development. Gelled fuel (pure and energized with nano-Al/B/C particle substitution) mixture with metal catalysts were formulated to examine its hypergugility with ignition delays on the order of 1–30 ms in most of cases, which are comparable with the existing liquid hyperguglic bipropellant systems. The minimum ignition delay time was recorded for boron case at 1.33 ms. And the calculated activation energy for the gelled fuel with pure and energetic particle substitution system resided within the range of 7–13 kJ/mol along with shear thinning behavior. Temperature profile also indicated an exothermic nature of the propellant system with 1000 to 1600 K recorded. Parameters such as apparent viscosity of the fuel, drop height and drop volume also played an important role for the hyperguglicity of the system in a drop experiment. It was also observed that the formation of a cage encapsulating the high temperature gases in a network formed by the gelling agent could result in a longer ignition delay.

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1. Introduction

The term hypergugility is the spontaneous ignition of a fuel and an oxidizer in contact. Hyperguglic propellants are preferred for several rocket propulsion missions, mostly when multiple and reliable ignitions are required for mission success [1].

Ethanol and hydrogen peroxide based hyperguglic bipropellant system can impart several properties that can contribute system advantages when compared to the traditional hyperguglic system such as unsymmetrical dimethylhydrazine-Red fuming nitric acid (UDMH-RPNA), monomethylhydrazine-nitrogen tetroxide (MMH–NTO) etc. [2]. It has high density, low vapor pressure, less toxic, corrosive and ecofriendly nature. Additionally, the hydrogen peroxide decomposition and combustion products with ethanol are non-toxic and environmentally more friendly than traditional hyperguglic systems which are in current use. However, the hydrogen peroxide provides some challenges too along with a number of advantages such as thermal stability, storage, handling and material compatibility.

The interest in using an alternative and more ecofriendly fuel and oxidizer system (such as ethanol and hydrogen peroxide) in rocket propulsion application has been renewed over the past decades [2–7]. Ethanol was selected based on its application in past as a rocket fuel such as German V-2 missile, Jupiter C, American Redstone Rocket, etc. In addition, the ethanol is a biofuel, which is least negative to the environment, easy to handle and transport, cheap and economical. Moreover, the hyperguglic bipropellant system based on catalytically promoted gelled ethanol fuel and hydrogen peroxide requires very less quantity of catalyst for its hyperguglicity and produces non-toxic the combustion products from the reaction which are mostly water vapor and CO2 gas with less than 1 mole% of metal catalyst oxide in solid form. On the contrary, a higher concentration of transition metal catalyst can reduce the exhaust velocity and specific impulse, since the exhaust velocity is inversely proportional to the square root of the average molecular weight of the exhaust product. In order to maximize the specific impulse, a reduction of the transition metal concentration of the fuel is required without affecting the ignition delay time of the hyperguglic system. The use of catalysts for promoting decomposition and combustion of hydrogen peroxide (80% concentrated) with methanol fuel dates back to German use of calcium permanganate as a hyperglic combination in the Me163 [8]. Also, recently a study has been done in which fuel additives were introduced for the purpose of ignition delay control specially for ethanol and peroxide systems [9]. For keeping a prospective for rocket system, a critical concentration of catalyst was considered for the study.
Current study also employed this approach, using a metal catalyst for hypergolic ignition.

The ignition delay time (ID) is a critical parameter for hypergolic propulsion system design such as an injector design and starting sequence which leads to application limitations, e.g. spacecraft system with a reaction control system, that uses thrusters to provide attitude control, must have ignition delays to allow multiple starts and stops within 100 ms to meet mission requirements. The time between fluid contact and ignition is a function of mixing, chemical kinetics, heat transfer, initial temperature, ambient temperature, and other local environmental conditions. Especially, for a gel propellant system where viscosity and viscoelastic properties play a vital role [3–7,10–16], the gel system has to overcome flow resistance before mixing to initiate ignition and chemical reaction [17–20]. Several studies have been performed to understand the effect of various parameters on ID of hypergolic liquid systems. However, very less or few efforts have been made on gelled and metalized gelled propellants as far as its hypergolicity, ignition delay and combustion studies are concerned [21]. Such gelled systems (metalized and pure case) have a marked difference in their physio-chemical properties in comparison to the traditional hypergolic liquid propellants which may lead to significant changes in their ignition and combustion behaviors. In past, the initial testing combinations for hypergolicity study were done through a drop test by dropping one or more of the propellant into a small volume of the other propellant while observing the subsequent reaction behavior [22–29]. Logically, the drop testing should provide a best environmental condition for repeatability of experimental results, although it should be recognized that the drop testing may differ considerably from the end application which includes aggressive mixing process [30].

Many diagnostic tools have been used in the past in the drop testing, such as photodiode, spectroscopy, shadowgraphy, Schlieren and high speed imaging. This article presents a discussion of hypergolicity and ignition delay experimental studies with the use of high speed camera photography to determine decomposition, ignition location and ignition delay times of gelled ethanol fuel (both pure and energized) and metal catalyst mixture with hydrogen peroxide. This would provide a significant insight into the ability to provide a reliable hypergolic ignition condition in practical conditions in future.

In the present study the formulated ethanol gel fuel (both pure and energized) requires less wt% of the thickening agent for gelation than the ones mentioned in the literature [3,4]. Regarding the hypergolicity, the main focus is on studying the least wt% of the transitional metal catalyst required for achieving hypergolicity with ease of suspension and reasonable ignition delay for a gel bipropellant system. Finally, the current study examines the hypergolicity and reasonable ignition delay using a visco-elastic material with parent fuel property of ethanol, whereas the previous papers primarily used the liquid ethanol fuel with hydrogen peroxide for hypergolicity.

2. Materials and methods

2.1. Materials

For the experimentation, the ethanol (99.8% pure, CAS No. 64-17-5, Sigma Aldrich Corp., South Korea) was used as a base fuel with cellulose derivative (propyl cellulose) as a gelling agent. The first fuel gel sample comprises 6 percent by weight of the gelling agent (Molecular weight 370,000, Powder, with 20 mesh particle size), which is considered as a pure case, while for energized case, 4 percent by weight of gelling agent and 4 percent by weight of nano-sized energetic particles were suspended [Al (100 nm), B (200–250 nm), and C (50 nm)], and all the samples were referred in the nomenclature and hereafter will be represented as SP, SAl, SB and SC, respectively. The percentages for gelling agent and energetic nano-particles are based on critical values for pure and energized cases. These critical values are ones at which the gel properties are maintained, i.e., if less gelling agent is added, the formulated fuel will behave like liquid, which is not desired. Hence, an introduction of the thickening agent above the critical value for gelation can help to overcome the liquid like behavior. The formulated gel fuel under normal conditions acts as semi-solid which behaves like a jelly, but with applied force or heat they tend towards liquid.

The oxidizer used was a propellant grade liquid hydrogen peroxide (90%) and was stored in a refrigerator at a temperature of about 0–2°C. Also the oxidizer was kept in a clean and light free environment in order to make sure no contamination
delay a speed file studied. reaction,
Main of Methods energized (C time camera 
Sigma chloride Aldrich. of
1.2. after. Sigma Aldrich Corp., South Korea), Manganese(II) acetylace-
chloride hydrous (CuCl₂·2H₂O, 99.999% pure, CAS No. 7447-39-4, Sigma Aldrich Corp., South Korea), or Manganese(II) acetylacetone (C₁₀H₁₄MnO₄, CAS No. 14,024-58-9, Sigma Aldrich). These catalysts will be represented as CCAT and MCAT respectively, hereafter.

2.2. Methods and experimental setup
Main focus of the study was to understand the gel viscosity behavior, hypergolicity and ignition delay of the formulated gel based bipropellant system. Temperature behavior due to chemical reaction, which plays a vital role in the ignition delay time, was also examined. Using the rotational rheometer (HAAKE RheoStress 6000, by Thermo-Scientific, Germany), the viscosity behavior was studied. The hypergolicity, ignition delay and the temperature profile of the bipropellant system was observed and recorded using a DSLR camera and a high speed camera, Photron SA-X2. A high speed camera used was calibrated for 5000 frames per second with a total run time of 4.3678 s, capturing 21,839 frames. The ignition delay time calculation is based on the frame number of the drop impact to the frame number of first visible flame multiplied by the time taken for each frame. As for the temperature profile, the K type thermocouples by OMEGA Corporation were used with a bead diameter of 0.127 mm with Teflon insulation, while for the thermocouple wire, the diameter measured is 0.11 mm. The data acquisition rate for measuring the temperature using thermocouples was set to 13 ms (sampling rate) from PC DAQ card. This is the fastest possible sampling rate achieved with the PC DAQ card system. These thermocouples are long enough so no additional copper wires were added and directly connected to the data acquisition card PDAQ56. A setting was made in such a way that the acquisition delay is 13 ms, and the main focus of the DAQ card is to measure temperature profile of the flame, not to study ID. This DAQ card has 10 analog input channels for thermocouples with a minimum scan rate of 0.007 Hz up to 80 Hz. A very small bead size of thermocouple might not introduce significantly a large error while the radiation has a minimum effect. The temperature profile irregularities were due to too slow data acquisition rate. The experimental setup used for the hypergolicity and ignition delay studies is shown in Fig. 1. The ignition delay was measured based on the time from the oxidizer drop impact on the fuel bed to the point when a visible flame appears. In the ignition study the ambient gas is air. However, it does not participate in the initial ignition transient, while it plays a role in continuous combustion on the fuel bed.

Using an injector of 17 gauge (17 gauge represents the internal diameter of the injector of 1.5 mm in diameter) with circular edge, the oxidizer drop was introduced from the height of 173 mm, directly on top of the gelled fuel bed on a thin quartz glass slide. The mass of fuel-catalyst mixture (99 wt% fuel and 1 wt% catalyst) placed on the glass slide was about 0.06–0.07 g. To record the temperature, thermocouples were placed at three different positions. Firstly, at the fuel bed, secondly at a vertical distance of 3 mm from the bed and finally at about 9 mm from the bed. Directly perpendicular to the plane, the high speed camera was placed, focused at the gelled fuel bed and the injector.

The injector was selected in order to produce a consistent drop diameter of about 3 mm which is approximately 0.014 ml in volume. However, the study was performed based on two parameters, firstly a drop impact study and secondly by introducing two different volumes of oxidizer, one drop of 0.014 ml or multi-drops of 0.05 ml on the fuel bed bed (multi-drops represent a fixed
volume of 50 μl which is equal to 0.05 ml. This experimental setup was designed to study the hypergolicity, ignition delay and temperature profile of the formulated bipropellant system with pure or energetic gelled fuel using two different catalysts and its overall performance.

3. Results and discussion

3.1. Apparent viscosity and activation energy study

The effect of applied shear rate (0–20 1/s) on the apparent viscosity of the gelled ethanol fuel is plotted in Fig. 2. The applied shear rate is shown to break down the gel network system so that the apparent viscosity decreases in the formulated gelled and energized ethanol fuels with some yield point (shear thinning behavior). In this experiment, a constant shear rate of 100 1/s was applied, when the temperature of the sample was varied from 0 to 70 °C so that the effect of the temperature on the gelled ethanol fuel for pure and energized cases was investigated. Figure 3 shows the apparent viscosity of all the gels measured as a function of the temperature. It is to be noted that 70 °C is the boiling point of the parent fuel (ethanol) over which it may cause the fuel to evaporate and finally to be ignited. Figure 3 shows the Arrhenius plots of (lnη) versus the inverse temperature for all of the ethanol gel fuel systems following Eq. (1).

\[ \eta_{\text{ap}} = A e^{Ea/RT} \] (1)

where “A” is a constant related to molecular motion, while “Ea” the activation energy for viscous flow at a constant shear rate, “R” is the gas constant, and “T” is the absolute temperature in “K”.

The apparent viscosity as a function of temperature study indicates that an exposure to higher temperatures provides the gel system with thermal energy, resulting in a decrease in the gel structural strength and a decrease in the apparent viscosity. Ea helps to determine the minimum amount of energy required for structural network breakdown while incurring a flow initiation in the gel and also for deducing the sensitivity of a gel to the applied temperature. For the current experimentation, Ea is comparatively higher for Sg than Sa, Al and Sp as seen in Table 1.

<table>
<thead>
<tr>
<th>Gel propellant</th>
<th>Activation energy (Ea) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sg</td>
<td>71 ± 0.03</td>
</tr>
<tr>
<td>Sa</td>
<td>80 ± 0.01</td>
</tr>
<tr>
<td>Sb</td>
<td>9.9 ± 0.01</td>
</tr>
<tr>
<td>Sc</td>
<td>12.3 ± 0.04</td>
</tr>
</tbody>
</table>

Table 1. Ea of the gelled and metalized ethanol fuels.

Since the delay is varying with the composition for both pure and energized case, it is obvious that the rate of liberation of minimum ignition energy is the controlling factor in determining the ignition delay. It may, however, be mentioned that the minimum ignition energy, which is the threshold energy content of the system required to initiate ignition, is dependent on a number of factors such as nature of fuel, its composition, exothermic reactivity with oxidizer, nature of energetic gaseous products, nano-energetic particle additives, thickening agent, and type of catalyst too.

3.2. Hypergolicity

Efforts were made to design a hypergolic gelled bipropellant system using gelled ethanol fuel with pure and energized cases, by introducing liquid hydrogen peroxide as an oxidizer in the presence of a suitable catalyst. It was observed that all the formulated gelled ethanol fuel (pure and energized), i.e., Sg, Sa, Sb and Sc fuel systems become hypergolic with the addition of 1 wt% CCAT or MCAT catalyst.

In order to observe the hypergolicity of the formulated gelled bipropellant system, a simple test was conducted using a quartz cup with a height of 20 mm and diameter of about 10 mm by introducing a fixed volume of gelled fuel for each case, which is 0.1 ml, whereas the oxidizer was introduced from a height of about 173 mm. It resulted in a positive display of hypergolic behavior for both catalysts as shown in Figs. 4–7.

Hypergolicity, observed with a rapid decomposition followed by ignition with varying delay times for respective fuel systems, was recorded by the DSLR camera (Figs. 4–7). The delay could be due to the varying visco-elastic nature, suspended metal particles and the gel network system of the pure and energized gel fuel.

Figures 4–7 show the hypergolicity study for ethanol gel pure and boron case with CCAT/MCAT catalyst mixture. Similar study was performed for the other cases too. It was observed that all the formulated gel compositions ignite spontaneously. Since the delay is varying with the composition for both pure and energized case, it is obvious that the rate of liberation of minimum ignition energy is the controlling factor in determining the ignition delay. It may, however, be mentioned that the minimum ignition energy, which is the threshold energy content of the system required to initiate ignition, is dependent on a number of factors such as nature of fuel, its composition, exothermic reactivity with oxidizer, nature of energetic gaseous products, nano-energetic particle additives, thickening agent, and type of catalyst too.

Detailed understanding of the ignition delay time of the respective gelled system and the temperature profile behavior is to be discussed in the following section. Due to the formation of cavitation between fuel and oxidizer as well as bubbling of oxidizer in the cup before ignition and stable combustion occur, this setup...
may not be appropriate for the ignition delay studies, however it gave a promising feedback of hypergolicity of the formulated gelled bipropellant system, with a flame height averaging from 80 to 150 mm with bright blush-green flame in case of fuel-CCAT mixture and purple-yellowish flame in the case of fuel-MCAT mixture. Also, bright energetic particle spikes could be observed in the energized cases as in Figs. 6 and 7.

### 3.3. Ignition delay

The results on the variation of ID for pure and energized ethanol gels (Al, B, C) with CCAT and MCAT mixture are tabulated in Table 2. As previously mentioned, the drop testing can help in the repeatability of replicating experiments, preliminary tests were done to evaluate test parameters such as drop height, drop volume, fuel volume and dropping oxidizer into fuel bed to ascertain a measure of the sensitivity of parameters in the experiments. When dropping the peroxide into the fuel bed, the ignition location was always just at the point of impact and above the fuel surface. In this drop test, experiment was performed with sufficient amount of fuel for the oxidizer drop in order to avoid sensitivity to the local mixing in our tests.

The process of ignition of a hypergolic bipropellant system is directly dependent on rate of chemical reaction and consequently heat liberation. Lower ID could be due to a more liberation of heat energy whereas only a certain minimum amount of energy may be required to initiate ignition. As for the energetic nano particle based gel system, the rate of reaction and heat liberation would increase due to higher exothermic reactivity and higher value of heat of combustion, which ultimately may become very faster due to a rise in temperature, finally resulting in reducing the ignition delay. However, the catalyst and metal type as well as its particle size also play a vital role in determining the ignition delay in energized case.

The gelation of ethanol would result in an increase in magnitude of physical properties such as viscosity and surface tension, which would hinder the mixing process of fuel and oxidant. The oxidizer after coming into contact with the gelled fuel would react locally at the surface of the gel. This would cause the decomposition and oxidative degradation of the thickening agent molecules, resulting in the exposure of fuel to oxidizer. The diffusion of the oxidizer into the gelled fuel may be initially slower but would increase as the apparent viscosity decreases with a rise in temperature of the system. Since the net amount of oxidizer available for reaction with gelled ethanol fuel would be less due to a utilization of a certain proportion in degrading thickening agent molecules, the ignition delay data in the case of gel would be higher than the pure liquid fuel.

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**Table 2**

Ignition delay of pure and metalized gelled ethanol fuel with hydrogen peroxide.

<table>
<thead>
<tr>
<th>Gelled fuel</th>
<th>Oxidizer quantity</th>
<th>Ignition delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₆ CCAT</td>
<td>Single drop</td>
<td>Rapid decomposition, No ignition</td>
</tr>
<tr>
<td>S₇ CCAT</td>
<td>Multi drop</td>
<td>50</td>
</tr>
<tr>
<td>S₇ MCAT</td>
<td>Single drop</td>
<td>13.46</td>
</tr>
<tr>
<td>S₈ CCAT</td>
<td>Multi drop</td>
<td>19.8</td>
</tr>
<tr>
<td>S₉ CCAT</td>
<td>Single drop</td>
<td>4.15</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Multi drop</td>
<td>28.7</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Single drop</td>
<td>47.7</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Multi drop</td>
<td>7.0</td>
</tr>
<tr>
<td>S₉ CCAT</td>
<td>Single drop</td>
<td>115.0</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Multi drop</td>
<td>90.0</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Single drop</td>
<td>37.0</td>
</tr>
<tr>
<td>S₉ MCAT</td>
<td>Multi drop</td>
<td>1.33</td>
</tr>
<tr>
<td>S₁₀ CCAT</td>
<td>Single drop</td>
<td>24</td>
</tr>
<tr>
<td>S₁₀ CCAT</td>
<td>Multi drop</td>
<td>14.35</td>
</tr>
<tr>
<td>S₁₀ MCAT</td>
<td>Single drop</td>
<td>19.2</td>
</tr>
<tr>
<td>S₁₀ MCAT</td>
<td>Multi drop</td>
<td>18.8</td>
</tr>
</tbody>
</table>

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Fig. 9. Cage network breakdown and ignition delay.

Fig. 10. Hypergolicity and ID study of Ethanol/B/MCAT with multi drop (0.05 ml).
Fig. 11. Temperature variation for various propellant systems at three vertical locations.
It was observed that when the gelled fuel was brought in contact with liquid oxidizer, a copious amount of gases was liberated first, showing the occurrence of exothermic reaction at the surface of contact due to inter-diffusional mixing behavior of the propellants through gel network before ignition, and then the hypergolicity was noticed after the liquefaction of gelled propellant.

Table 2 presents a comparative summary showing the dependence of ID on gelation, metallization, type of energetic nano particles, catalyst type and oxidizer volume. It is clearly seen that an incorporation of thickening agent in ethanol gel fuel affected its hypergolicity and ID. The addition of nano energetic particles in the gel system further affected the hypergolic nature of the fuel system and also ID data based on the type of energetic particles, their sizes, catalyst type and respective exothermic reactivity of metal particles blended in the ethanol gel system. In the case of boron, the particle size is approximately 250 nm. Its bigger particle size in comparison to Al and C, could be the reasons for a longer ignition delay in comparison to the other pure and energetic gel systems.

In the case of hypergolic bipropellant ignition in which the hydrogen peroxide is utilized as an oxidizer, it could be characterized by two different reactions, i.e., the exothermic decomposition of the peroxide and the local auto-ignition of heated oxygen and the fuel vapor. The formulated hypergolic system is a catalytically promoted hypergolic propellant system which is composed of energetic gel fuel and transition metal salt mixture (CCAT/MCAT). The suspended metal salt in the fuel catalytically decomposes hydrogen peroxide, producing superheated oxygen and water vapor. The exothermic decomposition of hydrogen peroxide provides the energy for heating and vaporizing the gel fuel and superheated oxygen then reacts with fuel vapor to initiate ignition and stable chemical reaction between the oxidizer and fuel, if the auto-ignition temperature of the fuel vapor is exceeded [25–28].

Among the catalytically driven fuels, the salts (transition metals) of Cu(II) and Mn(III) suspended in a fuel are particularly reactive with 90% H₂O₂. The exothermic decomposition of the hydrogen peroxide is a chemical process which uses a catalyst to speed up desired oxidation reaction of propellants (fuel and peroxide). Hydrogen peroxide serves as an oxidizing agent in the combustion of organic fuel. The driving force behind these reactions is the conversion of oxygen in the –1 oxidation state to –2 oxidation state. Furthermore, the hydrogen peroxide is weakly acidic in nature (pKₐ = 11.65). Under basic conditions, the peroxide loses a proton and becomes much less stable. Hence, fuels, that are strongly reducing agents and also basic in nature, would facilitate this conversion and thus be very reactive with hydrogen peroxide [29]. Schumb et al. [31] describes several classes of organic compounds that are reportedly hypergolic with hydrogen peroxide. Among those mentioned were compounds containing hydroxyl groups, with electron rich areas on the molecule that can act as reductants with hydrogen peroxide (such as ethanol with pKₐ = 16, pKₐ = −1.9). In addition, the suspension of catalyst (transition metal salts; Cu⁺², Mn⁻³) can markedly increase the rapid vaporization and temperature rise while promoting the exothermic reaction between fuel and peroxide. Another important feature of catalytically promoted hypergolic propellant system is the miscibility of fuel with the oxidizer. Miscibility is also an important factor as the oxidizer must penetrate into the gel fuel to maximize contact area with the fuel and catalytic material. Hydrogen peroxide is highly miscible in ethanol due to its polar nature. It was observed experimentally that, when hydrogen peroxide was introduced to pure liquid ethanol and gel ethanol, a rapid decomposition occurred without ignition. But, when catalyst (transitional metal salt such as CCAT/MCAT) was suspended into these systems, the ignition was noticed after a rapid decomposition in gel fuel system.

However, sometimes a rapid decomposition does not lead to hypergolicity as seen in the pure ethanol gel with CCAT for the single drop case in Table 2, since the rate of liberation of minimum ignition energy (known as threshold energy) was not sufficient enough to initiate ignition. If ID is increasing with energetic nano particle substitution, then it is evident that the increase in the ID with nano particle addition is solely due to the presence of type of energetic particle and exothermic reaction by catalyst type and fuel mixture.

When switching to multi drop from single drop test, the additional oxidizer concentration may increase the rate of reaction and heat liberation, but simultaneously delay the attainment of local minimum ignition energy level, which might be due to a dissipation of heat liberated to the excess of oxidizer for its vaporization and decomposition. Since the process of ignition of a bipropellant system is directly dependent on the rate of chemical reaction and consequent heat liberation, a fact that some thermal energy out of the heat liberated taken away by the excessive oxidizer would lower the local enthalpy of the mixture (fuel-oxidizer vapor and decomposed energetic gaseous products), results in an increases the ignition delay time. Since the delay is varying with composition as in Table 2, it is obvious that the rate of liberation of minimum ignition energy is the controlling factor in determining the ID. However, due to the presence of catalyst promoting a rapid decomposition, it was noticed that the ignition delay for the energized ethanol gel fuel mixture with both the catalyst (CCAT and MCAT) is lower for multi drop than single drop test except for Al-CCAT case.

The observed ignition delay and temperature profile for all the systems in the existing setup are within the range of 1–30 ms and 1000–1600 K, with the maximum ignition temperature recorded for S₂ CCAT (multi drop, 1620 K) and the minimum ignition delay for S₂ MCAT (multi drop, 1.33 ms) (Figs. 8–11 and, Table 2). Regarding the temperature profile in Fig. 11, for all the energized cases with CCAT the higher temperature was recorded than that with MCAT. However, it was opposite for the temperature profile recorded for pure gel case. In Fig. 11, initially a continuous rise in temperature for all the formulated system was observed until the maximum temperature was recorded at both positions, 2 and 3. The measured ignition delay for S₂, S₂Q, S₈ and S₈ hypergolic bipropellant system resides well within the range of existing liquid hypergolic bipropellant system as in Table 2, except for the case for S₈ CCAT (1 drop and multi drop) for which the observed ignition delay was 115 and 90 ms. The longer ignition delay might be due to a prolonged breakdown time in the gel network as shown in Fig. 9. Moreover, the energetic nano particle type and size may be also another reason for the delay time.

4. Conclusions

An experimental test was performed to determine whether a shear thinning ethanol gelled fuels (pure and energized) explored in this study were hypergolic or not with hydrogen peroxide (90%). One percent of two different catalysts such as copper chloride hydros (CCAT) and Manganese(II) acetylacetonate (MCAT) was introduced into fuels. Fuel-catalyst mixtures were tested and their relative reactivity in terms of hypergolicity and ignition delays was determined by using the high speed imaging technique. All the fuel-catalyst mixtures were found to react with peroxide quickly and violently after various ignition delays.

The apparent viscosity study showed the shear thinning behavior of the gel fuels with experimentally estimated activation energy within the range of 7–13 kJ/mol. The observed ignition delay was within the range of 1–30 ms which is comparable with those existing in liquid hypergolic bipropellant systems except for S₈ CCAT mixture case (1 drop and multi drop). Temperature profiles also
indicated an exothermic nature of the candidate gel propellant with a high temperature level within 1000–1600 K range at atmospheric conditions. Gelled ethanol fuel (pure and energized system) with CCAT or MCAT were found to be a promising hypergolic combination for bipropellant, having the low toxicity, high density, and reasonably short ignition delay.

Acknowledgment

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2014R1A2A2A01007347). Dr. Jyoti was also supported by the Korean Research Fellowship Program funded by the Ministry of Science, ICT and Future Planning through the National Research Foundation of Korea (No. 2015H1D3A1061637).

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