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Research Article

Preliminary Assessment of Hydrogen Peroxide Gel as an Oxidizer in a Catalyst Ignited Hybrid Thruster

Jeongmoo Huh ¹, Botchu V. S. Jyoti,² Yongtae Yun,³ M. N. Shoaib,³ and Sejin Kwon ³

¹School of Engineering and Materials Science, Queen Mary, University of London, Mile End Road, London E1 4NS, UK

²Department Space System Engineering, Faculty of Aerospace Engineering, TU Delft, Kluyverweg 1, 2629 HS Delft, Netherlands

³Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

Correspondence should be addressed to Sejin Kwon; trumpet@kaist.ac.kr

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In regard to propulsion system applications, the stability of liquid propellants in long-term storage is of increasing importance, and this had led to a greater interest in gelation technology. As part of a preliminary test to determine the feasibility of using a gel propellant in a rocket with a catalyst bed, a hybrid rocket with a catalyst reactor using a gel propellant as an oxidizer was tested for the first time in this study. Experiments were conducted with two different oxidizers: one with liquid phase hydrogen peroxide and the other with gel phase hydrogen peroxide, as well as high-density polyethylene as fuel for a 250 N class hybrid thruster performance test. The thruster was designed with the catalyst ignition system, and a catalyst was manufactured to be inserted into the catalyst reactor to facilitate oxidizer decomposition. While the test result with neat hydrogen peroxide indicated sufficient decomposition efficiency using a manganese dioxide/alumina catalyst and successful autoignition of the fuel via the decomposed product, gel hydrogen peroxide exhibited insufficient decomposition and there were difficulties in operating the thruster as a part of the catalyst was covered in the gelling agent. This preliminary study identifies the potential challenges of using a gel phase oxidizer in a catalyst ignited hybrid thruster and discusses the technical issues that should be addressed in regard to a gel propellant hybrid thruster design with a catalyst reactor.

1. Introduction

Today, many applications of chemical rockets are based on price competitive propulsion systems, as new cost-focused space industries have emerged and the commercial space technology which has been developed by such companies as Virgin Galactic, Space X, Blue Origin, Rocket Lab, and PLD Space features reusable and low-cost launch vehicles [1–7]. Even small-scale university-based sounding rockets rely on economic and safe propulsion systems for the efficient operation of sounding rockets as CanSat carriers. There is a hybrid rocket which is economical, safe, and reliable, and it is an attractive choice for space propulsion as it has the advantages of both solid and liquid rocket propulsion systems. Many previous hybrid rocket applications [8–16],

from lab-based sounding rockets to spaceships, demonstrate their advantages.

Chemical rocket propulsion is classified into three different propellant types: solid, liquid, and hybrid. While the oxidizer and fuel phase in solid and liquid rockets is identical, in a hybrid rocket the phases differ. In most hybrid rockets, the oxidizer is in liquid state and the fuel solid state. Solid rockets boast system simplicity, but a premixed oxidizer and fuel make them explosive. On the other hand, the separation of two propellants in hybrid rockets makes them safer, and by adjusting the propellant flow rate thrust generation can be controlled. They also permit re-ignition and have a potential advantage in terms of specific impulse performance compared to solid rockets. Although they have a lower specific impulse than liquid rockets, hybrid rockets confer benefits,

as they only need a tank, supply line, and fluid control devices for half of the propellants that liquid propellant rockets need.

A hybrid rocket gets even simpler depending on ignition systems. There are two types of hybrid rockets with different ignition types: one with a spark ignition device or torch and the other with a catalyst bed for the exothermic reaction of one of the propellants. The temperature of the catalyst bed is high enough, and autoignition of the fuel is feasible without an additional ignition source. Without a certain sequence for ignition, a catalyst ignited hybrid rocket has greater ignition reliability, as well as a system configuration which is simpler than that of spark or torch ignited rockets.

One of the most commonly used oxidizers in catalyst ignited hybrid rockets is a high-concentration solution of hydrogen peroxide, which is well known as high-test peroxide. Storability of this green propellant has been dramatically improved since its first major use as a propellant in the 1950s [17]. As a result, a large body of research advocates the use of H_2O_2 as a propellant for propulsion systems [10, 11, 18–21]. However, there are still challenges with regards to the long-term storability of H_2O_2 and even the effect of the stabilizing agents on H_2O_2 propulsion performance is an issue as described in [22].

Today, gelation technology attracts much interest [23–31] for its potential to increase enthalpy using metal particles as additives, deliver greater stability, and increase storability in respect of liquid propellants. The gel propellant has increasing viscosity at a decreased shear rate in a storage, which can contribute to the storability of hydrogen peroxide as well. Several studies [23, 24, 26, 31–34] have reported the hydrogen peroxide gelation process, which has been mainly for better stability and storability of H_2O_2 without any additives of metal powders, and possibility of use of the H_2O_2 gel as a hypergolic propellant combination. However, little research has been reported in regards to gel propellant decomposition. Given the fact that the energy of hydrogen peroxide usually is released by exothermic reaction by a catalyst, a study for gel propellant decomposition by a catalyst is essential for a wider range of usages of the gel. Unlike previous gel propellant studies in a fundamental and elemental approach, such as for gelation process, combustion behavior, and other basic characteristics, a study for the gel propellant decomposition by a catalyst must be conducted in a practical and systematic approach due to the sensitivity of a catalyst to reaction temperature and pressure, especially when a heterogeneous catalyst is used in a rocket in a working condition of relatively high temperature and pressure.

In this regard, a gel propellant has been tested to determine the feasibility and potential difficulties in using a gel phase propellant in a propulsion system with a catalyst reactor. As hydrogen peroxide is one of the most commonly used oxidizers in a catalyst ignited hybrid thruster, and due to potential combustion of an organic gelling agent used, this study has focused on the use of hydrogen peroxide gel in a hybrid rocket with a catalyst bed. For this preliminary test of a gel hybrid thruster, a hybrid rocket propulsion system was designed and manufactured to be tested using both neat and gel high-test peroxide for performance comparison. After the test results had been

established, the feasibility and possible challenges of using a gel propellant as an oxidizer in a catalyst ignited thruster were discussed, followed by the design requirement of a catalyst reactor and desirable performance of a gel for its wider range of usages as a propellant.

2. Design of the Propulsion System

2.1. Gel Propellants and Gelling Agents. Gel propellant is a solid-like liquid propellant whose rheological properties are altered by the addition of a gelling agent through an internal three-dimensional network that stems from physical and/or chemical bonds. Gel propellant is essentially a non-Newtonian fluid, and its shear thinning behavior, decreasing viscosity under shear strain, is desirable in a rocket propellant. Its behavior resembles a solid propellant in storage, where there is no shear stress, with greater stability and safety due to reduced vapor buildup from the solid-like liquid and the lower likelihood of leaks, which improves the long-term operational performance of a propulsion system with the propellant. Under shear stress, however, its viscosity decreases and it flows like a fluid on demand; therefore, unlike a solid propellant, it is throttle-able which makes it applicable to various mission profiles. Gel propellant also has advantages with regards to system configuration as it has a higher density than that of neat liquid propellant, which not only improves density-based specific impulse performance but also reduces the required tank volume. By adding metal additives such as boron, magnesium, or aluminum powder to a gel propellant, even higher performance can be achieved. One of the problems associated with using a solid propellant, crack occurrence in a solid fuel grain, can also be addressed by using a gel phase propellant.

As the viscosity increases with the addition of a gelling agent, however, the resulting high feeding pressure requirement, insufficient atomization, and low combustion efficiency cause problems. To overcome these challenges, many previous gel studies [23, 24, 29, 33–54] reported various formation methods for gel propellants, rheological properties, atomization, ignition, and combustion characteristics.

In those studies particularly interested in injector designs and the atomization characteristics of gel propellants [41–44, 46, 55, 56], water gel was often used as a gel simulant, in which case carbopol, polysaccharide, or xanthan gum was used as a gelling agent for water gel fabrication. But there are numerous formation methods reported with various propellants and gelling agents, e.g., some alcohol family fuels [33]; kerosene-based fuels such as JP-1 [50], JP-8 [26, 37, 39], and RP-1 [37]; and hydrazine-based fuels including monomethyl hydrazine (MMH) [29, 39, 53, 57, 58] and unsymmetrical dimethylhydrazine (UDMH) [35, 51] as a fuel, red fuming nitric acid (RFNA) [57], inhibited red fuming nitric acid (IRFNA) [26, 39, 58], and hydrogen peroxide [23, 26] as an oxidizer, methyl cellulose (MC) [25, 35, 51, 59–61], ethyl cellulose (EC) [35], propyl cellulose (PC) [32, 33], carboxymethyl cellulose (CC) [35], hydroxypropyl cellulose (HPC) [39, 53, 57], hydroxyethyl cellulose (HEC) [26], hydroxymethyl cellulose (HMC) [35], hydroxypropyl methylcellulose (HPMC) [29, 59], tetraglyme [53],

propylene glycol [35], fumed silica [26, 27, 29, 30, 37, 39, 53, 58], thixatrol st with xylene [38, 40, 45, 62], aerosol [50], guar gum [50], agarose [30], polyvinylpyrrolidone (PVP) [30, 63], and a mixture [30, 63] of fumed silica with agarose or PVP as a gelling agent depending on the gelation process of the propellants.

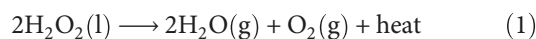
When selecting the propellant for gelation, it is worth noting that despite the rising demand for green propellants, toxic materials are still considered for use as rocket fuel, since gel phase fuels have the advantage of improved safety and result in less vaporization compared to liquid phase fuels. These combinations of different gelling agents and propellants are summarised in Table 1. Some of them are organic materials, which are more effective at increasing enthalpy during the combustion process than propellants gelled with inorganic gellants. Adding more gelling agents than required during the gelation process will increase the viscosity of gel property, which renders it more difficult to spray and atomize and reduces the enthalpy of the propellant. Accordingly, the weight percent of the gelling agent is a critical factor in the gelation process. Therefore, adequate weight percentages for the gelling agents previously used are also added to the table, most of which accounted for a small percent in the propellants (approximately 4% on average).

In regard to the hydrogen peroxide gel, the formation methods, rheological behavior, and feasibility of using hydrogen peroxide as a hypergolic gel propellant have been investigated [23, 24, 26, 31–34, 39]. Jyoti and Baek [23] reported the formation of hydrogen peroxide gel with a fumed silica gelling agent and measured the rheological properties of the gel propellant, including shear thinning and thixotropic behavior. They discovered that hydrogen peroxide gel has thixotropic characteristics with no significant variations, depending on a certain range of temperature variations. The thixotropic behavior of hydrogen peroxide gel was also observed by Rahimi et al. [26] during the gelation process of several oxidizers and fuels in their laboratory-scale gel propulsion technology research. For the hypergolic gel propellant combination, a catalyst or hypergolic substance for hydrogen peroxide has been introduced to the fuel gelation process, which is attracting significant interest among several research groups [24, 31–34]. Connell et al. [27, 34] fabricated and tested gel hydrocarbon fuels such as n-dodecane, n-heptane, and kerosene with particle mixtures including sodium borohydride (NaBH_4), which is a hypergolic material with hydrogen peroxide, and investigated the ignition delay characteristics of the H_2O_2 /fuel mixture. Shoaib et al. [31, 33] prepared alcohol family fuels such as ethanol, propanol, butanol, pentanol, hexanol, and heptanol, which were then gelled with organic gelling agent propyl cellulose and featured hypergolic additives and hydrogen peroxide. The ignition characteristics were subsequently examined. Ethanol fuel was gelled with a cellulose derivative containing energetic nanoparticles and metal catalysts, such as copper chloride hydrous ($\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$) and manganese acetylacetonate ($\text{C}_{10}\text{H}_{14}\text{MnO}_4$), and the ignition time was examined with hydrogen peroxide for the hypergolic bipropellant systems [32]. This test was also repeated for an ethanolamine-based fuel gelled with polyvinylpyrrolidone (PVP) and fumed silica

(SiO_2) containing energetic materials. This test featured the same catalyst for the hypergolic test with hydrogen peroxide [63]. Natan et al.'s [24] research featured the gelation of kerosene with a suitable gelling agent and sodium borohydride for the hypergolic ignition of hydrogen peroxide, and the ignition time was measured. Volker Weiser et al. [50] observed a droplet combustion of gelled mono- and bipropellants, which included a nitromethane/hydrogen peroxide mixture as a monopropellant, nitromethane, aluminized JP-1, iso-octane, and kerosene as the fuel and hydrogen peroxide, RFNA, ammonium nitrate, or mixture with water as an oxidizer with gelling agents such as aerosol and guar gum. These studies successfully demonstrated the formation, rheological behavior, and feasibility of using a hydrogen peroxide gel in a hypergolic gel propellant combination. However, despite the fact that a catalyst is often used to decompose hydrogen peroxide, little research has focused on the decomposition and combustion of gel phase hydrogen peroxide in a propulsion system. In this regard, a preliminary test on hydrogen peroxide gel is arguably warranted. A hydrogen peroxide gel was prepared based on the previous fabrication process [23] using cellulose as a gelling agent, which accounted for 5 wt% of the propellant tested.

2.2. Thruster Design. Among the various possible propellants for a hybrid rocket, such as nitrous oxide (N_2O), nitrogen tetroxide (N_2O_4), liquid (LO_2) and gas oxygen (GO_2), and hydrogen peroxide (H_2O_2) as an oxidizer and polymethyl methacrylate (PMMA), hydroxyl-terminated polybutadiene (HTPB), polyethylene (PE), polybutadiene (PB), polyvinyl chloride (PVC), and paraffin as fuel, the propellant combination of H_2O_2 /PE was adopted in this work, since hydrogen peroxide has several advantages as an oxidizer.

It has high density, which enhances density-based specific impulse performance and reduces the size of the oxidizer tank by as much as approximately half that of a rocket which uses nitrous oxide as an oxidizer [64]. It is a storable liquid propellant, and it is less burdensome in regard to storage insulation than cryogenic propellants such as liquid oxygen. Moreover, unlike nitrogen tetroxide, it is an environmentally friendly propellant whose by-products, oxygen, and water vapor pose few ecological risks. The decomposition process can begin at room temperature with a suitable catalyst, as shown in the equation below, which comprises heat energy of 2884 kJ/kg for 100 wt% hydrogen peroxide.



In addition, upon decomposition the temperature of rocket grade hydrogen peroxide (e.g., 749°C for 90 wt% H_2O_2) is high enough to facilitate autoignition of the aforementioned fuels, which approximate to 460°C for PMMA, 340°C for HTPB, 350°C for PE, 420°C for PB, 560°C for PVC, and 200°C for paraffin. The solid fuel grain in a hybrid rocket combustor should possess an adequate thermal strength to prevent escape from the chamber without enough combustion during operation, as such a phenomenon reduces combustion efficiency [65]. Polyethylene is not only easily accessible and processible at low cost but also thermally

TABLE 1: Propellant and gelling agent combinations from previous studies.

Research interest	Research group	Propellant/gelling agent	Gelling agent wt%	
Formation and rheological characteristics	Varghese et al., 1995 [35]	Kerosene/cabosil (fumed silica), cabosil and propylene glycol (PG), agar agar, methyl cellulose, organophilic clay complex (OPC), and OPC and PG Unsymmetrical dimethyl hydrazine (UDMH)/agar agar, ethyl cellulose, carboxymethyl cellulose, hydroxymethyl cellulose, and methyl cellulose	0.7-17	
	Teipel and Foerter-Barth, 2004 [36]	Nitromethane/silicon dioxide	4-8	
	Richard Arnold et al., 2009 [37]	JP-8, RP-1/fumed silica	4-6	
	Klaus Madlener, 2009 [38]	Paraffin/thixatrol st Paraffin/Aerosil 200 Jet A-1/thixatrol st Ethanol/Methocel 311	3.5-7.5	
	Rahimi et al., 2010 [39]	Monomethyl hydrazine (MMH)/hydroxypropyl cellulose (HPC) Hydrazine/hydroxyethyl cellulose (HEC) JP-8/silica Inhibited red fuming nitric acid (IRFNA)/silica Hydrogen peroxide/silica Water/Carbopol	0.3-8	
	Dennis et al., 2013 [29]	Monomethylhydrazine (MMH)/hydroxypropyl cellulose (HPC), fumed silica, and mixture	2-6	
	Padwal and Mishra, 2013 [40]	Jet A1/thixatrol st and xylene	1-9	
	Jyoti and Baek, 2014 [23]	Hydrogen peroxide/fumed silica	6	
	Jyoti and Baek, 2014 [60]	Ethanol/methyl cellulose	8	
	Jyoti and Baek, 2014 [61]	Ethanol/methyl cellulose	4-9	
	Jyoti and Baek, 2016 [30]	Ethanolamine/agarose and polyvinylpyrrolidone (PVP), agarose and fumed silica, and PVP and fumed silica	1-10	
	John et al., 2017 [59]	Ethanol/methyl cellulose (MC) and hydroxypropyl methyl cellulose (HPMC)	2-6	
	Atomization	Green et al., 1991 [41]	Water/sodium hydroxide, acrylic acid polymer resin (Carbopol 941)	0.5
		Chojnacki and Feikema, 1994 [42]	Water/sodium hydroxide, Carbopol	0.5-1
Shai Rahimi, 1998 [43]		Water/-	0.3-1	
Rahimi and Natan, 2000 [44]		RP-1/-, water/-	0.3-1	
Kampen et al., 2007 [45]		Jet A-1/thixatrol st	7.5	
Baek et al., 2011 [46]		Water/Carbopol	0.1-1	
Yang et al., 2012 [47]		Water/polysaccharide	2	
Fu et al., 2014 [56]		Water/xanthan gum	1	
Fu et al., 2014 [48]		Water/polysaccharide	2	
Padwal and Mishra, 2016 [62]		Jet A1/thixatrol st and xylene	7.5	
Kim et al., 2017 [88]		Kerosene/thixatrol st	7.5	
Connell et al., 2018 [34]		N-Dodecane/fumed silica	2.85	
Guan et al., 2018 [89]		ADN/-	-	
Ignition and combustion behavior		Volker Weiser et al., 2005 [50]	Nitromethane, JP-1, iso-octane/Aerosil 200, guar gum	1-2
	Benveniste Natan and Solomon, 2010 [24]	Kerosene/nanosilica fumed powder	-	

TABLE 1: Continued.

Research interest	Research group	Propellant/gelling agent	Gelling agent wt%
	Varma and Jyoti, 2011 [51]	Unsymmetrical dimethyl hydrazine (UDMH)/methyl cellulose	3.5
	Mishra and Patyal, 2012 [52]	Jet A1/thixatrol st and xylene	7.5
	Solomon et al., 2013 [53]	Monomethylhydrazine (MMH)/hydroxypropyl cellulose (HPC), tetraglyme, and fumed silica	3
	Jyoti et al., 2017 [63]	Ethanolamine/polyvinylpyrrolidone (PVP) and fumed silica	6
	Naseem et al., 2017 [31]	Ethanol/cellulose derivative	6-8
	Jyoti et al., 2017 [32]	Ethanol/propyl cellulose	4-6
	Shoaib et al., 2018 [33]	Ethanol, propanol, butanol, pentanol, hexanol, heptanol/propyl cellulose	2
	Dennis et al., 2018 [57]	Monomethylhydrazine (MMH)/hydroxypropyl cellulose (HPC) MMH/fumed silica	3-6
	Connell et al., 2018 [27]	Red fuming nitric acid (RFNA)/fumed silica N-Heptane, kerosene/fumed silica	3
	Yasuhara et al., 1993 [58]	Inhibited red fuming nitric acid (IRFNA)/cab-o-sil (silica particles) Monomethyl hydrazine (MMH)/Klucel, hydroxypropyl cellulose (HPC) Monomethyl hydrazine (MMH)/hydroxypropyl cellulose (HPC) Hydrazine/hydroxyethyl cellulose (HEC)	-
Thruster test	Rahimi et al., 2004 [26]	JP-8/silica Inhibited red fuming nitric acid (IRFNA)/silica Hydrogen peroxide/silica Water/Carbopol	0.3-8
	Branden and Elzoghby, 2007 [25]	Ethanol/methyl cellulose	10

strong enough to maintain its structure in the combustion chamber, as it has performed well with hydrogen peroxide in previous studies [9–11, 18, 66, 67].

The thruster design process is initiated by calculating the theoretical combustion properties of the propellant, based on a chemical equilibrium analysis. The Chemical Equilibrium with Applications (CEA) code [68] developed by NASA was used to estimate the performance. Theoretical specific impulse, combustion temperature, and characteristic velocity were calculated at a frozen equilibrium and the optimum expansion condition for the propellant combination, hydrogen peroxide, and high-density polyethylene. In addition, the gelling agent weight percent was adjusted from 0 to 10% at different chamber pressures to understand the effects of the two variables on performance. The chamber pressure has a significant effect on the specific impulse, but not on the other properties. Accordingly, among the properties, only the theoretical specific impulse is drawn depending on the pressures in Figure 1. As the organic gelling agent works as a fuel, the oxidizer-to-fuel (OF) ratio in the figure includes the gellant as a fuel. Thus, the addition of the gelling agent above the optimum value of the OF ratio, such as 7.5 at a combustion pressure of 20 bar, lowers specific impulse performance, and vice versa when it is below the optimum value. The figure illustrates that the effect of the weight percent of the gelling agent on performance is not pronounced, in particular when the OF ratio is near the optimum condition, and that the optimum OF ratio varies depending on the

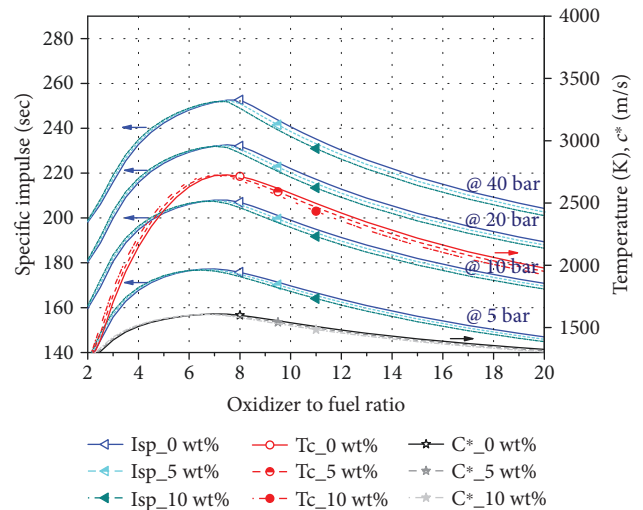


FIGURE 1: Estimated theoretical specific impulse (at different chamber pressures), combustion temperature, and characteristic velocity of the $\text{H}_2\text{O}_2/\text{HDPE}$ hybrid rocket depending on the weight percent of the gelling agent, cellulose.

combustion pressure, which is within the range of 6 to 8. The result well describes increasing specific impulse with increasing combustion pressure, but considering the high pressure drop at the feeding line especially when the gel

propellant is used, it was not intended to bring about a higher chamber pressure than typical of these small-scale propulsion systems [11, 67, 69]. As a result, it was determined to have 20 bar in this work. Since the performance of the neat and gel propellants was essentially the same near the optimum oxidizer-to-fuel ratio of 7.5 (e.g., 232.6 and 232.2 s as the specific impulse, 1602 and 1607 m/s as the characteristic velocity, and 2720 and 2727 K as the combustion temperature), only one design point (the gel) at the optimum OF condition was considered during the whole design process for the hybrid rocket that was supposed to be tested for each case of neat and gel propellant. From the estimated value of the specific impulse and the target thrust of 250 N, the required oxidizer flow rate was calculated as 110 g/s.

Unless there is an additional flow control device (such as a cavitating venturi tube) to suppress the effects of downstream pressure on upstream pressure, an oxidizer flow rate is determined by the difference between feeding pressure and combustion pressure. At the same time, the chamber pressure fluctuation possibly has an effect on the oxidizer flow rate, causing combustion instability. This phenomenon has been a critical issue in regard to pogo instability, and in extreme cases the positive feedback between combustion pressure and the propellant flow rate can ultimately cause system failure, especially when the natural frequency of the chamber structure matches the vibration of the propellant flow rate and combustion pressure, and resonance occurs. Therefore, an injector should be employed to act as a kind of pressure damper. To restrain the effect of chamber pressure fluctuation on the flow rate, the injector is expected to induce a pressure drop equal to 5–20% of that in the chamber [70]. Based on the required oxidizer mass flow rate for the thrust generation, the required injector hole area was estimated in the equation below, where C_d is the injector discharge coefficient, A the injector hole total area, ρ is the fluid density, and ΔP is the injector pressure difference.

$$\dot{m} = c_d A \sqrt{2\rho\Delta P}. \quad (2)$$

With the target injector pressure difference as 15% of the chamber pressure, the density of the oxidizer, and the discharge coefficient, the required injector hole area was estimated as 5.02 mm², and the injector was designed to have 33 holes of 440 μ m diameter as a showerhead-type injector.

In a catalyst reactor, an oxidizer is decomposed by a catalyst at a high enough temperature for autoignition of a fuel. The size of the catalyst reactor determines the flow rate the oxidizer is to be decomposed at, and this is important as reactors smaller in size than the optimum cause insufficient decomposition of the propellant; on the other hand, larger-sized catalysts decrease thruster efficiency due to the additional pressure drop caused by the additional catalyst. The catalyst capacity suggested by An and Kwon [19] and An [71], the decomposable propellant flow rate per catalyst reactor volume, was used to determine the adequate catalyst bed size. A catalyst capacity of MnO_x/Al₂O₃ was reported within a range of 2.5–2.6 g/(s·cm³) in the references [22, 72, 73], but a catalyst capacity of 2.0 g/(s·cm³) was considered in this work

for an oversized reactor as the gel propellant was expected to have less decomposition efficiency. The catalyst bed had a length of 33 mm in the shape of a cylinder, with a diameter of 45 mm.

Since a hybrid thruster is characterized by a low fuel regression rate and mixing inefficiencies, there are extra chambers, such as pre- and postcombustion chambers, which provide a recirculation zone so as to mitigate such problems and increase combustion efficiency. Due to the complex combustion phenomena which characterize a hybrid thruster, the regression rate of the fuel is commonly estimated based on empirical data in the form of the formula below as suggested in [74], where G represents propellant mass flux in the fuel port and x axial position of the fuel grain with constants of a , n , and m depending on combustion characteristics.

$$\dot{r} = aG^n x^m. \quad (3)$$

However, the regression rate is mainly affected by the mass flux rather than the axial position and the parameter for the axial location can be omitted. In this study, the experimental regression rate featured in a previous work [65] as shown below was used as a baseline, where G_o is the average oxidizer mass flux in the fuel port during combustion.

$$\dot{r} = 0.00915G_o^{0.78}. \quad (4)$$

A single port fuel was considered in the fuel design, which consists of an area two times bigger than the nozzle throat in accordance with the reference [69], and then the required port length was calculated. The reference also discusses the design of the pre- and postcombustion chambers, the diameter of which is three times bigger than the inner diameter of the fuel port. At the same time, the length of the postcombustion chamber is one-eighth the length of the fuel grain. In accordance with the recommended design procedure, the fuel port was designed with an inner diameter of 15 mm, an outer diameter of 45 mm, and a length of 275 mm. The pre- and postcombustion chambers have the same diameter as the outer diameter of the fuel, with lengths of 18 mm and 34 mm, respectively.

The nozzle was designed with a 60-degree contraction half angle in the converging section and a 15-degree conical expansion half angle in the diverging section, in accordance with recommendations made in the previous work [70, 75]. Assuming a one-dimensional isentropic flow through the nozzle with a design pressure of 20 bar at the nozzle inlet and 1 bar at the exit as well as the specific heat ratio of the product of combustion estimated by the CEA, the exit velocity at the nozzle is expected to be Mach 2.5. In addition, taking into account combustion temperature and the specific heat ratio, theoretical characteristic velocity was estimated and then the required nozzle throat diameter was determined as 11 mm. This estimate was based on the theoretical and experimental equation of characteristic velocity. Finally, the nozzle exit was designed for optimum expansion, for which the ratio of the nozzle exit and throat was 3.8.

In regard to the catalyst active material to effect hydrogen peroxide decomposition, there are various options, such as platinum [19, 76–82], iridium [20], ferrous chloride [83], silver [84–86], and manganese dioxide [10, 11, 18, 22, 66, 73, 81, 87]. In this study, manganese dioxide was chosen as the active material, because it has exhibited high decomposition efficiency for hydrogen peroxide, and it is relatively easily fabricated at low cost. Different kinds of silica, carbon, and alumina are possible candidates as a catalyst support, but gamma phase alumina was ultimately selected, as it has not only a high enough surface area for a catalyst reaction but also durability in the high-pressure and -temperature environment. In addition, it has reliability and good compatibility with the active material as reported [10, 11, 18, 22, 66, 73, 81, 87].

Catalyst support should be of an adequate size, since the size of the catalyst has an effect on thruster performance. If the catalyst support is too small, even though it has a high surface area to facilitate a chemical reaction and good decomposition efficiency, there will be high pressure loss in the catalyst reactor. On the other hand, if the support is too big, then it does not have sufficient efficiency for the propellant decomposition. Thus, in the first stage of the catalyst fabrication, γ -alumina pellets were ground and meshed to an appropriate size, which was 10–16 mesh (1.19–2.00 mm) in this research based on the good performance reported in the previous work [10, 69]. The crushed alumina support was washed with water and placed in a convection oven for 24 hours, before the loading of active material using 40 wt% sodium permanganate solution as a precursor. The alumina support wetted in the solution was dried at 120°C in the convection oven for 24 hours, before it was put into 500°C furnace for 5 hours as part of the calcination process to burn off undesirable organic materials potentially on the support. Finally, the catalyst was washed with water and dried again in the convection oven at 120°C for 24 hours. The fabricated catalyst was then inserted into the catalyst reactor of the thruster. A drawing of the designed thruster is shown in Figure 2, and the specification is summarised in Table 2.

3. System Setup and Experimental Test

The designed thruster was manufactured and integrated with a tank, valves, supply line, sensors, and a data acquisition system for the experimental test. Since one of the major potential applications of this gel hybrid rocket is a university-based sounding rocket, a stand-alone propulsion system was configured as simply as possible. This was also desirable in terms of determining the feasibility of this propulsion concept in the practical system configuration in the preliminary test as well as avoiding potential difficulties in reusing the feeding line in the event of gel propellant malfunction. A composite tank provided effective storage for both the pressurant and the oxidizer as part of a blow-down feeding system. The tank had an internal volume of 1.1 liters and the maximum allowable pressure of 300 bar, which was a high-pressure composite cylinder based on the aluminium liner with reinforced carbon and glass fiber manufactured by INOCOM Co., Ltd., South Korea. The tank was first filled with the

oxidizer, 90 wt% liquid, and gel phase hydrogen peroxide, respectively, for each case, and then the remaining volume was filled with the pressurant. The pressurant was nitrogen gas of 99.99% purity with an initial filling pressure of approximately 35 bar. The supplying line, which was 0.035 inches thick, consisted of stainless steel 316 tubes 3/8 inches in size. The feeding system comprised of a ball valve at the tank inlet for tank charging, a relief valve to effect safe operation at sub 50 bar pressure, and a pneumatic valve that was connected to a solenoid valve to activate the trigger signal for system operation.

Pressure and temperature sensors were used to understand the propellant flow rate, catalyst performance, combustion efficiency, and thruster performance. Six pressure sensors were installed between the tank inlet and the post-combustion chamber. With regards to the measurement of oxidizer flow rate, a flow measurement device, such as orifice plate or venturi tube, was not added to the system because those six pressure transducers were sufficient to estimate the oxidizer mass flow rate, under the assumption of a constant discharge coefficient of the feeding line, due to the known initial oxidizer mass in the storage. The simplicity of the system configuration without an additional flow meter was also desirable in terms of providing the same condition as possible for each experiment by reducing the effect of the difference in viscosity of the propellants. The PSH model pressure transducer, purchased from Sensys Corporation, was installed to measure the pressures at the tank inlet, catalyst reactor, precombustion, and postcombustion chambers. The sensors are known to have 0.054% accuracy with an upper limit of measurable pressure of 70 bar. The combustion temperature is expected to reach up to approximately 2450°C at the postcombustion chamber, which is out of the measurable temperature range of any type of thermocouple. However, the catalyst reactor temperature was measured as 90 wt% hydrogen peroxide and has a theoretical decomposition temperature of 749°C, which is within the measurable temperature range of a thermocouple. To measure the temperature at the catalyst reactor, a K-type thermocouple was used, which is one of the most commonly used temperature sensors and also easily accessible at low cost. The operation temperature for the thermocouple was between -270°C and 1370°C with 0.025°C resolution between -27°C and 1150°C and 0.1°C resolution between -220°C and 1370°C. Accordingly, only the temperature at the catalyst reactor was to be measured during the firing test, not the postcombustion chamber temperature, as the catalyst temperature measurement was essential to determine the decomposition efficiency of the propellant in the catalyst reactor. At the same time, the characteristic velocity based on the pressure measured in the postcombustion chamber could be used to evaluate thruster performance if needed. The pressure and temperature signals from the sensors during operation were obtained using a data acquisition system produced by National Instruments Co., Ltd. The thruster was manufactured with stainless steel 316, and the fabricated manganese dioxide catalyst, based on gamma alumina support, was inserted into the catalyst reactor. High-density polyethylene fuel grain was located in the combustion chamber, and a graphite nozzle was located

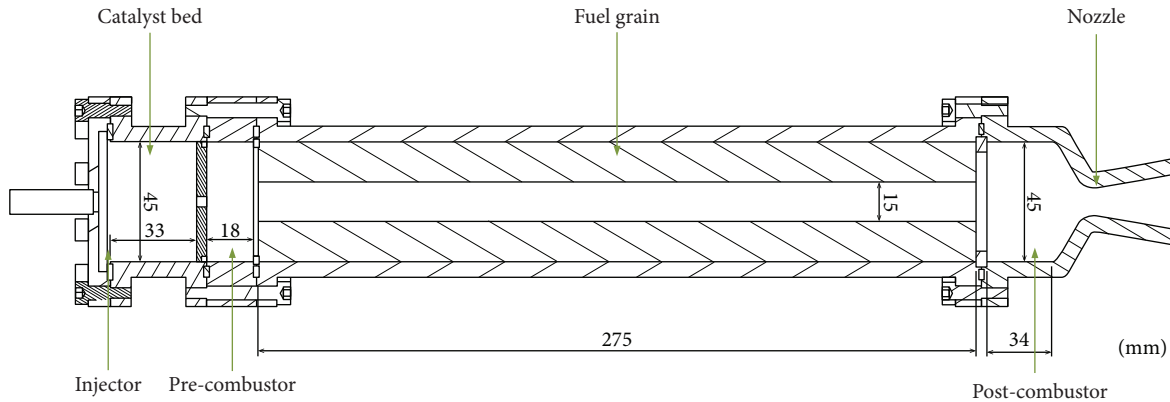


FIGURE 2: Drawing of the designed hybrid thruster.

TABLE 2: Result of the hybrid thruster design.

Thruster specification	
Thrust	250 N
Chamber pressure	20 bar
Oxidizer	H ₂ O ₂ (neat/gel)
Fuel	HDPE
O/F ratio	7.5
Specific impulse	232 s
Catalyst	MnO _x /Al ₂ O ₃
Catalyst capacity	2.0 g/(s·cm ³)
Catalyst support size	10-16 mesh

inside the nozzle case. The integrated propulsion system was installed at a thruster test stand with the thruster set horizontally and the rest set vertically, as shown in Figure 3. Using the prepared propulsion system, neat and gel hydrogen peroxide was tested as an oxidizer, the liquid form of which was purchased from Habo Chemical Co. Ltd., China. For safety purposes, the solenoid valve was triggered by an operator from a long distance and the pneumatic valve was operated by the signal from the solenoid valve, while an imaging device was recording the thruster operation.

4. Experimental Test Result and Discussion

The performance test of the hybrid thruster was conducted using neat and gel 90 wt% hydrogen peroxide, and the test results are shown in Figures 4–7. In the case of neat hydrogen peroxide, autoignition successfully occurred as shown in Figure 4(a). As shown in Figure 4(b), however, the decomposed gel propellant failed to autoignite the fuel, which indicated inferior decomposition efficiency of the gel propellant.

The pressure and temperature recorded during operation are given in Figures 5 and 6 for the neat and gel propellants, respectively. Among the pressures measured at the six different points, only three measured pressures were drawn in the figures as the others were in between them. Temperature was measured at three different points in the catalyst reactor in

order to determine its effectiveness in terms of both size and decomposition efficiency.

As described in Figure 5, the feeding pressure measured at the tank inlet referred to as “P1” gradually decreased during operation from an initial pressure of about 35 bar as the oxidizer was fed through a blow-down feeding system, i.e., the nitrogen gas which was used as a pressurant was expanding and decreasing in pressure as the oxidizer was being consumed in the tank. The precombustion chamber pressure “P2” and the postcombustion chamber pressure “P3” also gradually decreased, but the “P3” curve was less varied, since the pressure which built up at the precombustor deterred the oxidizer from overflowing, which was caused by the large pressure difference between the tank and the upstream part of the thruster at the early stage of firing. During operation, the average pressure recorded in the pre- and postcombustion chambers were 18.4 bar and 15.2 bar, respectively. In Figure 5, the pre- and postcombustion chamber pressure curves near the 4 s mark also provide information on the ignition delay characteristics of this hybrid rocket propulsion system. The liquid oxidizer flowed for approximately 4 s including an ignition delay of about 0.4 s, and the combustion lasted for roughly 3.6 s. The total fuel mass burned during the operation was 36.3 g, and the initial mass of the oxidizer stored in the tank was 360.0 g; therefore, the fuel consumption rate and the average oxidizer flow rate were approximately 10.1 g/s and 90.0 g/s, respectively. As a result, in the case of the neat propellant, the average oxidizer-to-fuel ratio during the firing test was 8.9, which was slightly higher than the designed OF ratio of 7.5. In the case of the gel propellant, the fuel was not autoignited due to insufficient propellant decomposition efficiency and the fuel was not consumed, whereas the oxidizer flow rate was almost the same as in the case of the neat propellant. The time average pressure during operation in the pre- and postcombustion chambers was 5.1 bar and 1.8 bar, respectively, the lower one of which was more or less the same as the choking pressure of the nozzle, illustrating it had barely maintained the choked flow.

In terms of the temperature profiles, the test result proved that the catalyst reactor was oversized, as the temperature “T2” measured in the middle of the catalyst reactor was the

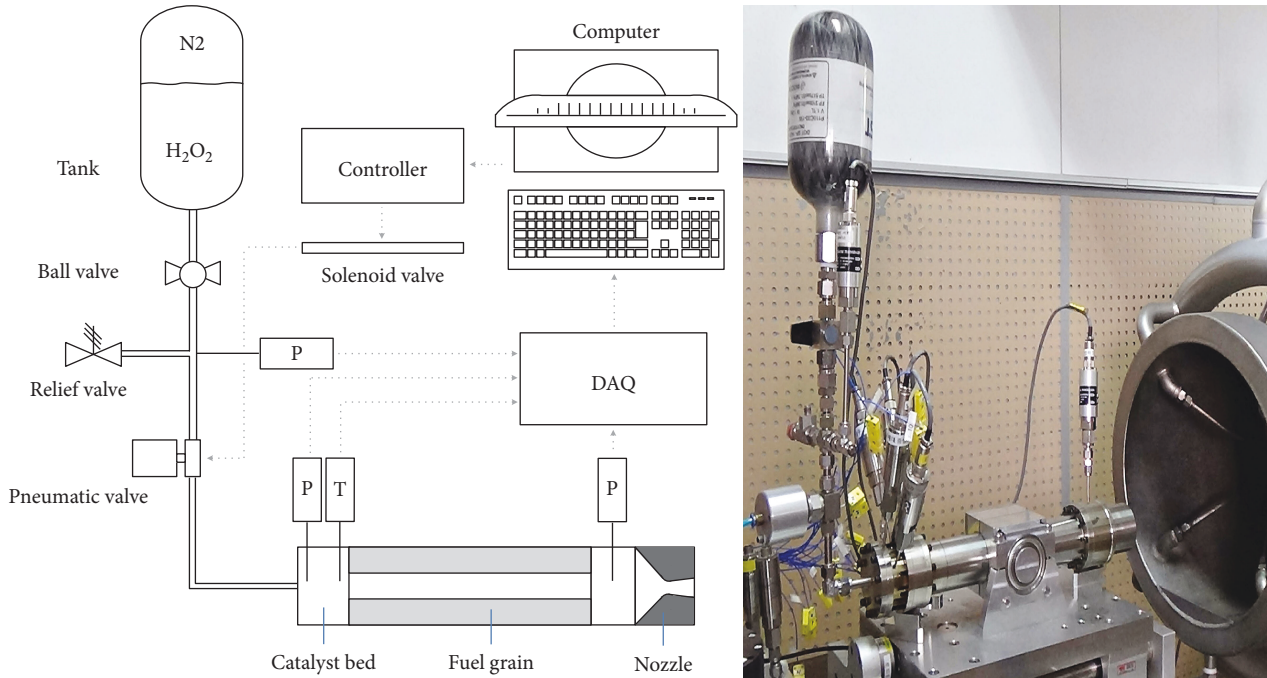


FIGURE 3: Experimental setup for the hybrid thruster performance test.

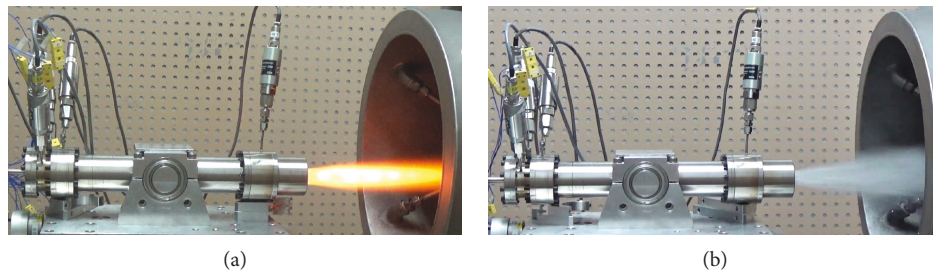


FIGURE 4: Firing test of the hybrid thruster using neat (a) and gel (b) phase high-test peroxide as an oxidizer.

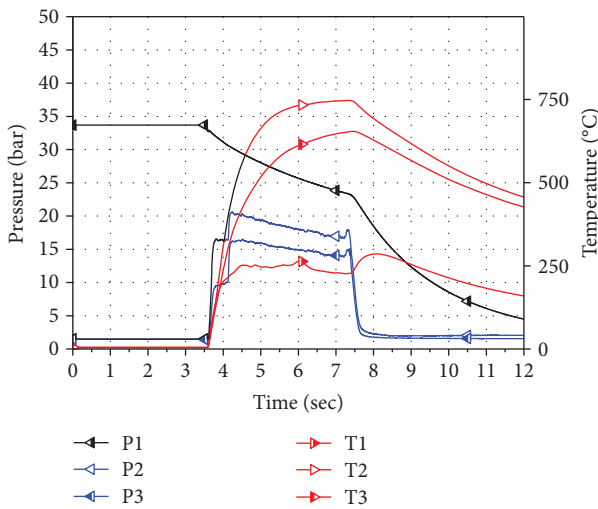


FIGURE 5: Test result of the hybrid thruster using neat H_2O_2 and HDPE (P1 at feeding line, P2 at precombustor, P3 at postcombustor, and T1-3 at the catalyst bed upstream to downstream).

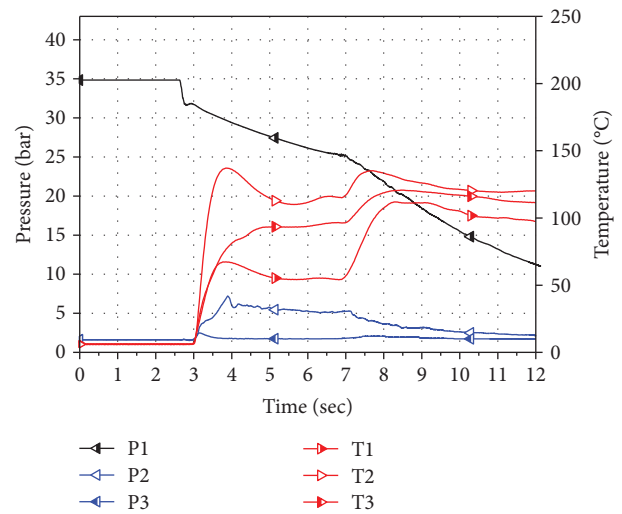


FIGURE 6: Test result of the hybrid thruster using gel H_2O_2 and HDPE (same notation as Figure 5).



FIGURE 7: MnO_x/Al_2O_3 catalyst after the firing test using neat (a) and gel (b) H_2O_2 .

highest temperature among the temperatures obtained in the catalyst reactor as shown in Figure 5. This result demonstrates that the part of the catalyst bed from where “T2” was measured to “T3” was unnecessary, because it only works to induce an additional pressure drop in the decomposed oxidizer in the catalyst bed during the operation. That was, however, intended in order to test the hybrid rocket with the gel propellant, which is expected to require a larger-sized catalyst reactor. The highest recorded temperature in the catalyst bed was $747^\circ C$, which was almost the same as the adiabatic temperature of the 90 wt% hydrogen peroxide, $749^\circ C$, and ensured sufficient decomposition efficiency of the fabricated manganese dioxide/alumina catalyst. In the case of the gel propellant, however, the maximum temperature was $139^\circ C$, which was much lower than that of the neat propellant. This was insufficient to facilitate autoignition of the fuel, high-density polyethylene, since it has an ignition temperature of approximately $380^\circ C$. But in this case as well, the highest temperature was measured in the middle of the catalyst reactor as noted by “T2” in Figure 6. This means that the catalyst reactor was not smaller in size than that required for the gel propellant. In fact, it was rather oversized as the temperature “T3” revealed a decreasing temperature in the downstream direction of the catalyst bed from the point where “T2” was measured.

While the incomplete decomposition of the gel propellant could stem from several technical issues, this result clearly shows it was not related to the size of the catalyst bed. The probable causes are arguably related to the following: the formation method of the gel propellant, rheological behavior, atomization characteristics, injector performance, catalyst decomposition efficiency and compatibility issue with the gel propellant, and combustion characteristics in regard to the fuel. Some of these issues have been reported in previous gel propellant studies aforementioned.

In regard to the formation method of the gel propellant, cellulose is one of the most frequently used gelling agents for various fuels as shown in Table 1. However, there are many alternative gelling agents with different weight percents. A greater amount of gelling agent increases the viscosity of the propellant, which affects not only atomization

behavior but also the enthalpy of the propellant regardless of whether it is an organic or inorganic gelling agent. In this regard, it is arguably advisable to experiment with different gelling agents of different weight percents to optimize the gel characteristics, in terms of rheological behavior, atomization, and decomposition efficiency. In addition, as a gel propellant is triggered to be liquefied under shear stress during initial flow within the supply lines on route to the injector, re-designing the feeding line to effect adequate shear stress is another option which could eliminate this problem. The design of the injector could also be modified in this regard. However, although atomization of the gel propellant can be improved using other types of injectors, such as the impinging jet injector [46, 55, 56, 62] and the swirl injector [47, 88, 89], those injectors should be employed with care, especially in a small-scale thruster with a catalyst bed, since they potentially increase the required ullage volume between the injector and the catalyst bed, which has a negative effect on the thrust-to-weight ratio, as described in the previous study [71].

Even if all those challenges are overcome based on the specific technical issues mentioned above, potential incompatibility between the gelling agent and the catalyst bed cannot be ruled out in the event one or the other does not meet a certain requirement. As an organic gelling agent, cellulose was expected to contribute to the combustion process in the chamber and leave the thruster through the nozzle as a product of the reaction, but due to an insufficient temperature in the catalyst reactor the gellant covered the surface of the catalyst which potentially restrained its reactivity. Figure 7 illustrates the difference in appearance of the catalyst after the firing process when neat and gel propellants are used. Whereas Figure 7(a) shows a relatively clear catalyst, Figure 7(b) shows the catalyst covered in the gelling agent. Thus, the first lesson from this result is that if an inorganic material is used as a gelling agent, which cannot contribute to the combustion process, it is incompatible with a thruster with a catalyst reactor for long-term operation.

A catalyst reactor with a high enough decomposition efficiency and temperature is essential to effecting the combustion of an organic gelling agent. However, as shown in

Figure 5, even the neat hydrogen peroxide recorded a temperature of approximately 250°C in a part of the catalyst reactor during operation which does not guarantee ignition of a gelling agent, which was cellulose in this work. It is possible that some parts of the catalyst reactor are lower in temperature than others and the gelling agent covers the part of the catalyst with incomplete combustion in a gel hybrid thruster, which can deteriorate repeatability of a catalyst performance. This concerns the original objective of this kind of system configuration: the long-term operation of a propulsion system using hydrogen peroxide gel with improved storability.

Therefore, the desirable characteristics of a gel as a propellant to be used in a catalyst ignited thruster is that the gelling agent should be an organic material and its ignition temperature should be sufficiently low so as not to remain on the surface of a catalyst. Use of a reactive gelling agent with a catalyst is also an option to circumvent the problem. To be compatible with a gel propellant, a catalyst reactor must have a higher temperature than the ignition temperature of a gelling agent with evenly distributed temperature without a low-temperature point, which will require a low aspect ratio design of the catalyst reactor. In terms of a catalyst active material, it should be highly reactive with a gel propellant. Thus, catalyst design using multiactive materials not only to facilitate the neat propellant decomposition but also to provide instant ignition or decomposition of the gelling agent upon contact should be beneficial. Instead of a heterogeneous catalyst installed in the reactor, use of a homogeneous consumable catalyst constantly supplied is also an option for the compatibility between a gel and a catalyst reactor.

Although the test result indicated difficulties of the use of the gel propellant in the state of the catalyst reactor, based on the requirement discussed in this preliminary test as a baseline, further studies are required to find the appropriate condition of a gel and a catalyst for their normal work, which will make the use of gel decomposition feasible for a wide range of gel propulsion system applications.

5. Conclusion

The major weakness of hydrogen peroxide as a propellant is arguably long-term storability, as there is still concern over its stability due to the potential problem of self-accelerated decomposition, which is caused by limited purity and storage temperature. Since gel propellants have enhanced the storability of liquid propellants, hydrogen peroxide gel was prepared and tested in this work. To determine the feasibility of the use of gel propellant, in particular as an oxidizer with greater stability for a hybrid rocket, a preliminary test featuring hydrogen peroxide gel with a catalyst ignited hybrid thruster was conducted. A hybrid thruster was prepared and performance tested using two different phases of hydrogen peroxide. While neat hydrogen peroxide exhibited sufficient decomposition efficiency via a manganese dioxide/alumina catalyst and successful autoignition of the fuel grain via the decomposed product, the gel propellant indicated insufficient decomposition and difficulties of reusability of the catalyst. In addition, in the case of the neat propellant,

the catalyst reactor performed well, but a part of the catalyst recorded a lower temperature than required for the ignition of the gelling agent. This addressed the potential difficulties of using a gel propellant in a thruster with a catalyst reactor and the design requirement for catalyst reactor for future applications of a gel propellant without the problems. This study first reports the results of using a gel propellant for a catalyst ignited thruster application. As this is a preliminary test for gel decomposition, the experimental data is not conclusive, but it does clearly demonstrate the requirement of a gel as a propellant and of a catalyst reactor to be compatible with a gel propellant. Additional tests adopting multifunctional catalyst active materials and more reactive gelling agents are suggested for the use of gel decomposition for various propulsion system applications and its long-term operation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

- [1] D. N. Baker and S. P. Worden, "The large benefits of small-satellite missions," *Eos, Transactions American Geophysical Union*, vol. 89, no. 33, pp. 301-302, 2008.
- [2] G. I. Crouch, T. M. Devlin, J. J. Louviere, and T. Islam, "Modelling consumer choice behaviour in space tourism," *Tourism Management*, vol. 30, no. 3, pp. 441-454, 2009.
- [3] D. Webber, "Point-to-point sub-orbital space tourism: some initial considerations," *Acta Astronautica*, vol. 66, no. 11-12, pp. 1645-1651, 2010.
- [4] Y.-W. Chang, "The first decade of commercial space tourism," *Acta Astronautica*, vol. 108, pp. 79-91, 2015.
- [5] T. J. Horvath, V. V. Aubuchon, S. Rufer et al., "Advancing supersonic retro-propulsion technology readiness: infrared observations of the SpaceX Falcon 9 first stage," in *AIAA SPACE and Astronautics Forum and Exposition*, Orlando, Florida, September 2017.
- [6] W. Peeters, "From suborbital space tourism to commercial personal spaceflight," *Acta Astronautica*, vol. 66, no. 11-12, pp. 1625-1632, 2010.
- [7] J. Loizou, "Turning space tourism into commercial reality," *Space Policy*, vol. 22, no. 4, pp. 289-290, 2006.
- [8] E. D. Jonny Dyer, Z. Dunn, K. Lohner et al., "Design and development of a 100km nitrous oxide/paraffin hybrid rocket

- vehicle,” in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Cincinnati, OH, USA, July 2007.
- [9] J. Huh, Y. Kim, Y. Yun et al., “Flight testing of a university based H₂O₂/HDPE hybrid sounding rocket at KAIST,” in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, USA, July 2017.
- [10] J. Huh, B. Ahn, Y. Kim, H. Song, H. Yoon, and S. Kwon, “Development of a university-based simplified H₂O₂/PE hybrid sounding rocket at KAIST,” *International Journal of Aeronautical and Space Sciences*, vol. 18, no. 3, pp. 512–521, 2017.
- [11] Y. Yun, J. Huh, Y. Kim, S. Kang, S. Heo, and S. Kwon, “Demonstration of 2,500 N-class H₂O₂/HDPE hybrid rocket for lab-scale sounding rocket,” in *2018 Joint Propulsion Conference*, Cincinnati, Ohio, USA, July 2018.
- [12] U. F. Mario Kobald, K. Tomilin, A. Petrarolo et al., “Sounding rocket “HEROS” - a low-cost hybrid rocket technology demonstrator,” in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, USA, July 2017.
- [13] B. Marciniak, A. Okninski, B. Bartkowiak et al., “Development of the ILR-33 “Amber” sounding rocket for microgravity experimentation,” *Aerospace Science and Technology*, vol. 73, pp. 19–31, 2018.
- [14] A. J. Boiron, O. Verberne, M. Faenza, and B. Haemmerli, “Hybrid rocket motor upscaling and development test campaign at Nammo Raufoss,” in *51st AIAA/SAE/ASEE Joint Propulsion Conference*, Orlando, FL, USA, July 2015.
- [15] K. M. Broughton, W. D. R. M. J. Brooks, and J. Pitot, “Development of the Phoenix-1B Mk II 35 km apogee hybrid rocket,” in *2018 Joint Propulsion Conference*, Cincinnati, Ohio, USA, July 2018.
- [16] R. DalBello, *Virgin Galactic: Creating Safe, Reliable, and Frequent Access to Space*, Springer, Vienna, 2017.
- [17] M. Ventura and G. Garboden, “A brief history of concentrated hydrogen peroxide uses,” in *35th Joint Propulsion Conference and Exhibit*, Los Angeles, CA, USA, July 1999.
- [18] B. Ahn, H. Kang, E. Lee, Y. Yun, and S. Kwon, “Design of multiport grain with hydrogen peroxide hybrid rocket,” *Journal of Propulsion and Power*, vol. 34, no. 5, pp. 1189–1197, 2018.
- [19] S. An and S. Kwon, “Scaling and evaluation of Pt/Al₂O₃ catalytic reactor for hydrogen peroxide monopropellant thruster,” *Journal of Propulsion and Power*, vol. 25, no. 5, pp. 1041–1045, 2009.
- [20] H. Tian, T. Zhang, X. Sun, D. Liang, and L. Lin, “Performance and deactivation of Ir/γ-Al₂O₃ catalyst in the hydrogen peroxide monopropellant thruster,” *Applied Catalysis A: General*, vol. 210, no. 1–2, pp. 55–62, 2001.
- [21] L. Torre, A. Pasini, L. Romeo, A. Cervone, and L. d’Agostino, “Performance of a monopropellant thruster prototype using advanced hydrogen peroxide catalytic beds,” *Journal of Propulsion and Power*, vol. 25, no. 6, pp. 1291–1299, 2009.
- [22] D. Jang, S. Kwon, and S. Jo, “Effect of phosphate stabilizers in hydrogen peroxide decomposition on manganese-based catalysts,” *Journal of Propulsion and Power*, vol. 31, no. 3, pp. 904–911, 2015.
- [23] B. V. S. Jyoti and S. W. Baek, “Rheological characterization of hydrogen peroxide gel propellant,” *International Journal of Aeronautical and Space Sciences*, vol. 15, no. 2, pp. 199–204, 2014.
- [24] V. P. Benveniste Natan and Y. Solomon, “Hypergolic ignition of oxidizers and fuels by fuel gelation and suspension of reactive or catalyst particles,” in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Nashville, TN, USA, July 2010.
- [25] J. Brandenburg and M. Elzooghby, “Ethanol gel based fuel for hybrid rockets: the Golden Knight Hybrid Rocket Program at the University of Central Florida,” in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Cincinnati, OH, USA, July 2007.
- [26] S. Rahimi, D. Hasan, and A. Peretz, “Development of laboratory-scale gel propulsion technology,” *Journal of Propulsion and Power*, vol. 20, no. 1, pp. 93–100, 2004.
- [27] T. L. Connell Jr, G. A. Risha, R. A. Yetter, and B. Natan, “Ignition of hydrogen peroxide with gel hydrocarbon fuels,” *Journal of Propulsion and Power*, vol. 34, no. 1, pp. 170–181, 2018.
- [28] P. C. Pinto, J. R. N. H, W. Naumann, A. Thumann, and G. Kurth, “Scalability of gelled propellant rocket motors,” in *7th European conference for aeronautics and space sciences (EUCASS)*, Milan, Italy, 2017.
- [29] J. D. Dennis, T. D. Kubal, O. Campanella, S. F. Son, and T. L. Pourpoint, “Rheological characterization of monomethylhydrazine gels,” *Journal of Propulsion and Power*, vol. 29, no. 2, pp. 313–320, 2013.
- [30] B. V. S. Jyoti and S. W. Baek, “Rheological characterization of ethanolamine gel propellants,” *Journal of Energetic Materials*, vol. 34, no. 3, pp. 260–278, 2016.
- [31] M. S. Naseem, B. V. S. Jyoti, S. W. Baek, H. J. Lee, and S. J. Cho, “Hypergolic studies of ethanol based gelled bi-propellant system for propulsion application,” *Propellants, Explosives, Pyrotechnics*, vol. 42, no. 6, pp. 676–682, 2017.
- [32] B. V. S. Jyoti, M. S. Naseem, and S. W. Baek, “Hypergolicity and ignition delay study of pure and energized ethanol gel fuel with hydrogen peroxide,” *Combustion and Flame*, vol. 176, pp. 318–325, 2017.
- [33] M. N. Shoaib, B. V. S. Jyoti, S. W. Baek, and J. Huh, “Effect of alcohol carbon chain on enthalpy of combustion and ignition delay time for gelled hypergolic propellant system,” *Propellants, Explosives, Pyrotechnics*, vol. 43, no. 5, pp. 453–460, 2018.
- [34] T. L. Connell Jr, G. A. Risha, R. A. Yetter, and B. Natan, “Hypergolic ignition of hydrogen peroxide/gel fuel impinging jets,” *Journal of Propulsion and Power*, vol. 34, no. 1, pp. 182–188, 2018.
- [35] T. L. Varghese, S. C. Gaindhar, J. David et al., “Developmental studies on metallised UDMH and kerosene gels,” *Defence Science Journal*, vol. 45, no. 1, pp. 25–30, 1995.
- [36] U. Teipel and U. Foerter-Barth, “Mechanical properties of gel propellants with nanoparticles,” *Journal of Energetic Materials*, vol. 22, no. 2, pp. 69–82, 2004.
- [37] P. H. S. S. Richard Arnold, T. Kubal, O. Campanella, and W. E. Anderson, “Investigation of gelled JP-8 and RP-1 fuels,” in *Proceedings of the World Congress on Engineering and Computer Science 2009 (WCECS 2009)*, San Francisco, USA, 2009.
- [38] H. C. Klaus Madlener, “Some aspects of rheological and flow characteristics of gel fuels with regard to propulsion application,” in *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Denver, Colorado, USA, August 2009.
- [39] S. Rahimi, A. Peretz, and B. Natan, “Rheological matching of gel propellants,” *Journal of Propulsion and Power*, vol. 26, no. 2, pp. 376–379, 2010.

- [40] M. B. Padwal and D. P. Mishra, "Synthesis of Jet A1 gel fuel and its characterization for propulsion applications," *Fuel Processing Technology*, vol. 106, pp. 359–365, 2013.
- [41] J. Green, D. Rapp, and J. Roncace, "Flow visualization of a rocket injector spray using gelled propellant simulants," in *27th Joint Propulsion Conference*, Sacramento, CA, USA, June 1991.
- [42] K. Chojnacki and D. Feikema, "Atomization studies of gelled liquids," in *30th Joint Propulsion Conference and Exhibit*, Indianapolis, IN, USA, June 1994.
- [43] B. N. Shai Rahimi, "Atomization characteristics of gel fuels," in *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Cleveland, OH, USA, July 1998.
- [44] S. Rahimi and B. Natan, "Flow of gel fuels in tapered injectors," *Journal of Propulsion and Power*, vol. 16, no. 3, pp. 458–464, 2000.
- [45] J. von Kampen, F. Alberio, and H. K. Ciezki, "Spray and combustion characteristics of aluminized gelled fuels with an impinging jet injector," *Aerospace Science and Technology*, vol. 11, no. 1, pp. 77–83, 2007.
- [46] G. Baek, S. Kim, J. Han, and C. Kim, "Atomization characteristics of impinging jets of gel material containing nanoparticles," *Journal of Non-Newtonian Fluid Mechanics*, vol. 166, no. 21–22, pp. 1272–1285, 2011.
- [47] L.-j. Yang, Q.-f. Fu, Y.-y. Qu, W. Zhang, M.-l. Du, and B.-R. Xu, "Spray characteristics of gelled propellants in swirl injectors," *Fuel*, vol. 97, pp. 253–261, 2012.
- [48] Q.-f. Fu, R.-z. Duan, K.-d. Cui, and L.-j. Yang, "Spray of gelled propellants from an impinging-jet injector under different temperatures," *Aerospace Science and Technology*, vol. 39, pp. 552–558, 2014.
- [49] D. L. Galecki, "Ignition and combustion of metallized propellants," in *25th Joint Propulsion Conference*, Monterey, CA, USA, July 1989.
- [50] S. G. Volker Weiser, S. Kelzenberg, N. Eisenreich, and E. Roth, "Investigations on the droplet combustion of gelled mono and bipropellants," in *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Tucson, Arizona, USA, July 2005.
- [51] M. Varma and B. V. S. Jyoti, "Ignition and combustion studies of heterogeneous UDMH-RFNA gel propellants," *International Journal of Energetic Materials and Chemical Propulsion*, vol. 10, no. 3, pp. 259–275, 2011.
- [52] D. P. Mishra and A. Patyal, "Effects of initial droplet diameter and pressure on burning of ATF gel propellant droplets," *Fuel*, vol. 95, pp. 226–233, 2012.
- [53] Y. Solomon, S. J. DeFini, T. L. Pourpoint, and W. E. Anderson, "Gelled monomethyl hydrazine hypergolic droplet investigation," *Journal of Propulsion and Power*, vol. 29, no. 1, pp. 79–86, 2013.
- [54] C. U. Kirchberger, A. D. Stiefel, M. Kurilov, and H. K. Ciezki, "Overview of recent gel propellant activities at DLR Lampoldshausen," in *2018 Joint Propulsion Conference*, Cincinnati, Ohio, USA, July 2018.
- [55] L.-j. Yang, Q.-f. Fu, W. Zhang, M.-l. Du, and M.-x. Tong, "Spray characteristics of gelled propellants in novel impinging jet injector," *Journal of Propulsion and Power*, vol. 29, no. 1, pp. 104–113, 2013.
- [56] Q.-f. Fu, L.-j. Yang, K.-d. Cui, and F.-c. Zhuang, "Effects of orifice geometry on gelled propellants sprayed from impinging-jet injectors," *Journal of Propulsion and Power*, vol. 30, no. 4, pp. 1113–1117, 2014.
- [57] J. D. Dennis, J. D. Willits, and T. L. Pourpoint, "Performance of neat and gelled monomethylhydrazine and red fuming nitric acid in an unlike-doublet combustor," *Combustion Science and Technology*, vol. 190, no. 7, pp. 1141–1157, 2018.
- [58] W. Yasuhara, A. Olson, and S. Finato, "Advanced gel propulsion controls for kill vehicles," in *Annual Interceptor Technology Conference*, Albuquerque, NM, USA, June 1993.
- [59] J. John, P. Nandagopalan, S. W. Baek, and A. Miglani, "Rheology of solid-like ethanol fuel for hybrid rockets: effect of type and concentration of gellants," *Fuel*, vol. 209, pp. 96–108, 2017.
- [60] B. V. S. Jyoti and S. W. Baek, "Formulation and comparative study of rheological properties of loaded and unloaded ethanol-based gel propellants," *Journal of Energetic Materials*, vol. 33, no. 2, pp. 125–139, 2014.
- [61] B. V. S. Jyoti and S. W. Baek, "Rheological characterization of metallized and non-metallized ethanol gel propellants," *Propellants, Explosives, Pyrotechnics*, vol. 39, no. 6, pp. 866–873, 2014.
- [62] M. B. Padwal and D. P. Mishra, "Characteristics of gelled Jet A1 sprays formed by internal impingement of micro air jets," *Fuel*, vol. 185, pp. 599–611, 2016.
- [63] B. V. S. Jyoti, M. S. Naseem, S. W. Baek, H. J. Lee, and S. J. Cho, "Hypergolicity and ignition delay study of gelled ethanolamine fuel," *Combustion and Flame*, vol. 183, pp. 102–112, 2017.
- [64] M. Toussaint, N. Cesco, F. Masson et al., "Development status of the 200N H₂O₂ thruster for a A5-ME upper stage reaction control system," in *Proceedings of Space Propulsion*, Cologne, Germany, 2014.
- [65] M. Lee, *Design and Performance Evaluation of Hydrogen Peroxide Oxidizer Hybrid Thruster for Sounding Rocket System*, Dept. Aerospace Engineering, Daejeon, Korea, 2014.
- [66] E. S. Jung and S. Kwon, "Autoignitable and restartable hybrid rockets using catalytic decomposition of an oxidizer," *Journal of Propulsion and Power*, vol. 30, no. 2, pp. 514–518, 2014.
- [67] J. Tsohas, L. J. Doppers, C. IV E G, E. M. Dambach, and S. D. Heister, "Progress in technology demonstration for a small hybrid launch vehicle," in *5th Responsive Space Conference*, Los Angeles, CA, USA, 2007.
- [68] S. Gordon and B. J. McBride, *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications*, NASA Reference Publication, Cleveland, Ohio, 1994.
- [69] S. Kang, "Design and performance evaluation of hybrid rocket using highly concentrated hydrogen peroxide," in *Dept. Aerospace Engineering*, KAIST, Daejeon, Korea, 2016.
- [70] D. K. Huzel and D. H. Huang, *Modern Engineering for Design of Liquid-Propellant Rocket Engines*, AIAA, SW, Washington DC, 1992.
- [71] S. An, "Design of H₂O₂ monopropellant thruster with consideration of response characteristics for attitude control system," in *Dept. Aerospace Engineering*, KAIST, Daejeon, Korea, 2010.
- [72] D. Jang, "Catalyst bed improvement of the hydrogen peroxide/kerosene bipropellant thruster for a long-term combustion," in *Dept. Aerospace Engineering*, KAIST, Daejeon, Korea, 2015.
- [73] D. Jang, S. Kang, and S. Kwon, "Preheating characteristics of H₂O₂ monopropellant thruster using manganese oxide catalyst," *Aerospace Science and Technology*, vol. 41, pp. 24–27, 2015.

- [74] G. Marxman, R. Muzzy, and C. Wooldridge, "Fundamentals of hybrid boundary layer combustion," in *Heterogeneous Combustion Conference*, Palm Beach, FL, USA, December 1963.
- [75] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*, John Wiley and Sons, Hoboken, New Jersey, 8th edition, 2010.
- [76] J. Lee and S. Kwon, "Evaluation of ethanol-blended hydrogen peroxide monopropellant on a 10 N class thruster," *Journal of Propulsion and Power*, vol. 29, no. 5, pp. 1164–1170, 2013.
- [77] A. Pasini, L. Torre, L. Romeo, A. Cervone, and L. D'Agostino, "Performance characterization of pellet catalytic beds for hydrogen peroxide monopropellant rockets," *Journal of Propulsion and Power*, vol. 27, no. 2, pp. 428–436, 2011.
- [78] J. Huh and S. Kwon, "Design, fabrication and thrust measurement of a micro liquid monopropellant thruster," *Journal of Micromechanics and Microengineering*, vol. 24, no. 10, article 104001, 2014.
- [79] J. Huh, D. Seo, and S. Kwon, "Fabrication of a liquid monopropellant microthruster with built-in regenerative micro-cooling channels," *Sensors and Actuators A: Physical*, vol. 263, pp. 332–340, 2017.
- [80] J. Huh and S. Kwon, "Microcooling channel effect on a monopropellant microelectromechanical system thruster performance," *Journal of Propulsion and Power*, vol. 33, no. 6, pp. 1591–1595, 2017.
- [81] W. Jung, S. Baek, T. Kwon, J. Park, and S. Kwon, "Demonstration of ethanol-blended hydrogen peroxide gas generator for ramjet combustor flow simulation," *Journal of Propulsion and Power*, vol. 34, no. 3, pp. 591–599, 2018.
- [82] S. Dolci, D. B. Dell'Amico, A. Pasini, L. Torre, G. Pace, and D. Valentini, "Platinum catalysts development for 98% hydrogen peroxide decomposition in pulsed monopropellant thrusters," *Journal of Propulsion and Power*, vol. 31, no. 4, pp. 1204–1216, 2015.
- [83] C. Xupeng, L. Yong, Z. Zhaoying, and F. Ruili, "A homogeneously catalyzed micro-chemical thruster," *Sensors and Actuators A: Physical*, vol. 108, no. 1-3, pp. 149–154, 2003.
- [84] D. Plumlee, J. Steciak, and A. Moll, "Development and simulation of an embedded hydrogen peroxide catalyst chamber in low-temperature co-fired ceramics," *International Journal of Applied Ceramic Technology*, vol. 4, no. 5, pp. 406–414, 2007.
- [85] S.-L. Lee and C.-W. Lee, "Performance characteristics of silver catalyst bed for hydrogen peroxide," *Aerospace Science and Technology*, vol. 13, no. 1, pp. 12–17, 2009.
- [86] P. Morlan, W. P. A. Nejad, D. Ruttler, R. Fuller, and W. Anderson, "Catalyst development for hydrogen peroxide rocket engines," in *35th Joint Propulsion Conference and Exhibit*, Los Angeles, CA, USA, June 1999.
- [87] S. An, S. Jo, J. Wee, H. Yoon, and S. Kwon, "Preliminary flight test of hydrogen peroxide retro-propulsion module," *Acta Astronautica*, vol. 67, no. 5-6, pp. 605–612, 2010.
- [88] H. Kim, T. Ko, S. Kim, and W. Yoon, "Spray characteristics of aluminized-gel fuels sprayed using pressure-swirl atomizer," *Journal of Non-Newtonian Fluid Mechanics*, vol. 249, pp. 36–47, 2017.
- [89] H.-S. Guan, G.-X. Li, and N.-Y. Zhang, "Experimental investigation of atomization characteristics of swirling spray by ADN gelled propellant," *Acta Astronautica*, vol. 144, pp. 119–125, 2018.

