Feasibility Study of Plasma Chemical Thruster

IEPC-2007-223

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: Monopropellant thruster utilizes hydrazine, which decomposes into hot gases by making contact with catalyst. Some of critical troubles were occurred due to the catalyst. In Addition, high toxicity of hydrazine make handling difficult. In order to overcome these problems, "plasma chemical thruster" was suggested in our study. Plasma chemical thruster utilizes electrical discharge chamber to decompose green propellant. In this paper, the feasibility of the plasma chemical thruster was evaluated. With a plasma chemical thruster, we constructed, it was confirmed that hydrogen peroxide decomposed by contact with arc plasma. And lower electrical power consumption will be required for practical application.

I. Introduction

MONOPROPELLANT thruster is one of the chemical thrusters, which is employed on majority of spacecrafts. As shown in Fig. 1, a monopropellant thruster composes a capillary tube, an injector, a catalyst bed and a nozzle. When hydrazine is fed through the capillary tube to the catalyst bed, hydrazine will auto-decompose into nitrogen, hydrogen and ammonia gases immediately. Since the dissociation reaction is exothermic, these gases will gain high enthalpy and contribute to the thrust improvement. Its relatively simple structure and principle for producing thrust make the monopropellant thruster system compact and high reliability.

The catalyst bed consists of iridium supported by porous alumina ceramics pellets ($\phi \approx 1.0$ mm), and is sandwiched by a pair of wire nets. Although hydrazine decomposition will be induced securely by making contact with the pelletized catalyst, the vibration at launch or the long-term operation of the thrust will frequently damage the catalyst. Then particulates of catalyst pass through the wire nets, and it will cause several critical problems like deterioration of the decomposition performance, or choke of the injector ($\phi \approx 0.1 \sim 0.5$ mm) or the capillary tube ($\phi \approx 0.5$ mm). Moreover, severe treatment of the catalyst has been required in the gravity field to avoid the particulates getting out of the catalyst bed and jamming the propellant feed line. In addition, since hydrazine has high toxicity, handling of hydrazine at ground facility is very severe and extra costs are required.

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In order to improve these characteristics and mitigate the restriction, improvement of catalyst and application of green propellant have been got attention and studied around the world [1-3]. In our study, electrical discharge was employed, instead of solid catalyst, for dissociating a monopropellant. And a thruster with this decomposition method was named “Plasma Chemical Thruster” (abbreviated as PCT). As previous study, it was confirmed that electrical discharge affected to induce hydrazine decomposition [4]. In this paper, the object is to evaluate the feasibility of the PCT with green propellant. Preliminary model of PCT was designed and constructed, and hydrogen peroxide was employed as a green propellant.

II. Plasma Chemical Thruster

A. Characteristic of Plasma Chemical Thruster

The concept of the plasma chemical thruster is shown in Fig. 2, schematically. Compared with arc jet thruster or MPD thruster, electrical discharge in PCT aims to induce the propellant decomposition. Therefore its thrust performance will depend on the propellant characteristics as well as a monopropellant thruster.

Table 1 shows target performances of PCT compared with other chemical and electric propulsion. Thrust and specific impulse will be the same as the chemical propulsion, and electrical power consumption will be the same as electric propulsion. And PCT will utilize green propellant. Therefore, PCT will obtain simpler handling of thruster system without careful of catalyst particulate and propellant toxicity at gravity field, although sub-kilowatt of electrical power will be required for a few newton of thrust.

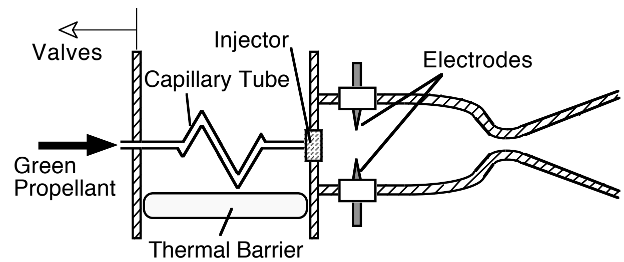

Figure 2. Schematic of plasma chemical thruster.

Table 1. Target characteristics of plasma chemical thruster compared with other thrusters.

Thruster		Thrust, N	Specific Impulse, s	Electrical Power Consumption, W	Features
Chemical Propulsion	Cold jet	< 1	< 100	0	simple structure
	Monopropellant	0.5 ∽ 400	220	∽10	catalyst, toxicity
	Bipropellant	5 ∽ 500	290	0	complex structure, toxicity
Electric Propulsion	Pulsed Plasma	∽ 0.001	300 ∽ 1000	10 ∽ 50	small impulse bit
	Registjet	0.2 ∽ 0.4	300	200 ∽ 500	catalyst
	Arcjet	∽ 0.25	500	1000 ∽ 3,000	catalyst
	Hall Thruster	0.350	1,000	∽ 5,000	large structure
	Ion Thruster	0.250	3,000	∽ 5,000	large structure
Plasma Chemical Thruster		1 ∽ 5	160 ∽	∽ 300	non-catalyst, lower toxicity
		5 ∽ 500	300	∽ 300	non-catalyst, lower toxicity

B. Green Propellant

Green propellant is a generic name of propellants that has low toxicity and kind to natural environment and human health. Hydroxyl Ammonium Nitrate (HAN) based propellant or hydrogen peroxide are under investigation around the world [2, 3].

Hydrogen peroxide progress the self-decomposition reaction, represented as follow.

$$H_2O_2(l) \rightarrow H_2O(g) + (1/2)O_2(g) + 54\text{kJ} \tag{1}$$

Since this reaction is exothermic, produced gases will have high enthalpy. In fact, however, hydrogen peroxide solution is utilized, so the following reaction will progress simultaneously,

$$H_2O(l) \rightarrow H_2O(g) - 44\text{kJ} \tag{2}$$

Since the reaction (2) is endothermic, some enthalpy generated from the reaction (1) will be absorbed by the reaction (2). As the result, hydrogen peroxide of over 64 % is required to induce auto-decomposition reaction. Addition to the characteristic, hydrogen peroxide and its decomposition products has much lower toxicity than hydrazine. These are the reason that hydrogen peroxide is attracted as a green propellant, alternative to hydrazine.

C. Preliminary Model of Plasma Chemical Thruster

Preliminary model of PCT, which was designed in this study, is shown in Fig. 3. This thruster was designed to generate a few newton of thrust. 60 wt% hydrogen peroxide was utilized as monopropellant with priority for handling convenience. As described above, because its concentration was too low to induce the chain reaction of its dissociation, direct current arc discharge was employed to overcome (compensate) the heat of vaporization of water of 40 wt% in the propellant. Electrodes, made by carbon, were arranged as well as an arc jet thruster as shown in Fig. 4. Rated output voltage and current of electrical power supply were 120 V and 10 ~ 35 A, respectively. Note that this thruster is for evaluating dissociation feasibility of hydrogen peroxide, and thruster performance will not be desirable.

In order to sustain the arc discharge, carrier gas was fed from upstream of the thruster. After the arc discharge was sustained stably, hydrogen peroxide was supplied from wall of the constrictor, as shown in Fig. 4. Then hydrogen peroxide would contact with the arc plasma. The effect of hydrogen peroxide decomposition was evaluated by chamber pressure and plume temperature (refer to section III).

This PCT had a reaction chamber to encourage the propellant decomposition at downstream of the constrictor. Then generated gases with higher enthalpy than supplied propellant was exhausted through the nozzle.

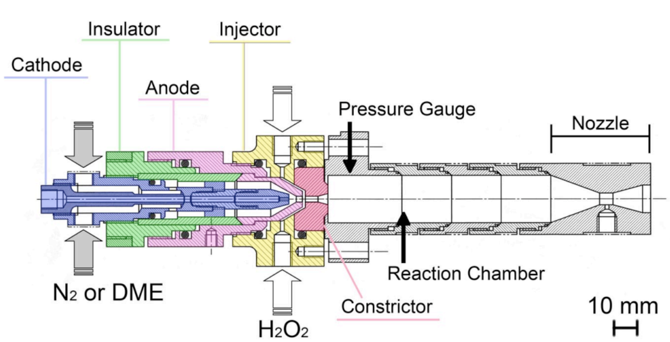

Figure 3. Preliminary model of plasma chemical thruster.

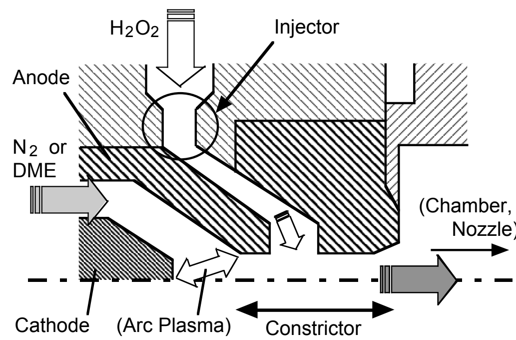

Figure 4. Electrodes configuration of the thruster in this study, refer to Fig. 3.

III. Experimental Setup

Table 2 shows the predicted performances of the thruster [5]. Addition to nitrogen gas, di-methyl ether (DME) was also utilized as carrier gas. DME has fuel characteristic, which is attracted as one of the clean fuel because soot would not produced through its combustion. In this study, it was expected that additional combustion energy, with hydrogen peroxide and DME, and improvement of thrust performance would be attained. Moreover, water, which corresponds to 0 wt% hydrogen peroxide, was utilized as propellant to clarify the effect of hydrogen peroxide decomposition.

Figure 5 indicates experimental system diagram in this study. Hydrogen peroxide was supplied to the thruster by regulated system with nitrogen gas. Note that DME has the vaporization pressure of about 0.6 MPa at room temperature, and it is as liquid that filled up to the storage tank when DME was required. And DME would vaporize through the feed pipe to the thruster. Pressure at the reaction chamber and temperature at the exhaust nozzle were measured by pressure gauge and thermo couple, respectively. And electrical discharge current and voltage were measured by current probe and high voltage probe, respectively.

Table 2. Predicted performance of H_2O_2 plasma chemical thruster with N_2 and DME plasma.

m_c [NL/min]	m_p [ml/min]	P_c [MPa]	F_{th} [N]
(N_2) 8	(H_2O_2) 170	0.30	4
(DME) 6.2	(H_2O_2) 91	0.41	5

m_c: carrier gas (fuel) flow rate
m_p: propellant (oxidant) flow rate
P_c: predicted chamber pressure (abs)
F_{th}: predicted thrust

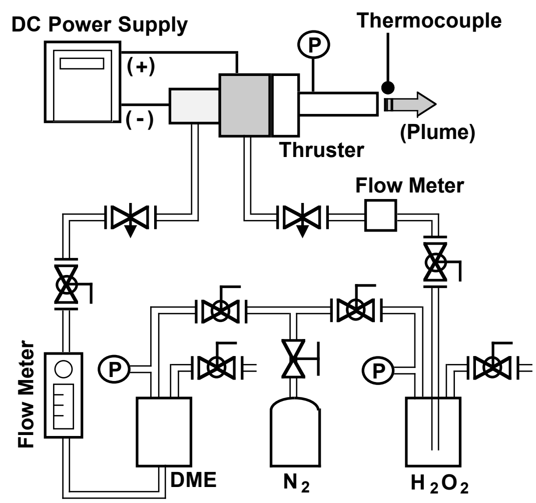

Figure 5. Experimental system diagram in this study.

IV. Results and Discussions

A. Effect of Hydrogen Peroxide with Nitrogen and DME Plasma

Experimental results were arranged in Table 3. When water was supplied to nitrogen arc plasma, pressure at the reaction chamber was not increased, as shown in Fig. 6. Note that, in Fig. 6, electrical discharge voltage was started to measure after its discharge was induced and stable. On the other hands, when hydrogen peroxide was fed to the arc plasma, increase of the chamber pressure and plume temperature were measured. As shown in Fig. 7, maximum chamber pressure reached about 1.4 atm (abs), where an oscillation of the pressure might be due to instability of the propellant flow. These results indicate that vaporization of hydrogen peroxide did not contribute the pressure increment but decomposition of hydrogen peroxide.

When DME and hydrogen peroxide were applied, further increase of the chamber pressure and plume temperature were measured, whereas no increment of the pressure was observed with DME and water. As shown in Fig. 8, the chamber pressure reached about 2.0 atm (abs) with stable electrical discharge. These results indicate that combustion energy was contributed in addition to the dissociation reaction of hydrogen peroxide.

Table 3. Experimental results of H_2O_2 plasma chemical thruster.

No.	m_c [NL/min]	m_p [ml/min]	P_d [kW]	ΔP_c [atm]	ΔT_{max} [K]
	(N_2)	(H_2O)			
1	8	50	1.4	0	41
	(N_2)	(H_2O_2)			
2	8	0	2.3	0	25
3	8	75	1.4	0.2	33
4	8	40 ~ 140	2.5	0.4	95
	(DME)	(H_2O)			
5	6.2	60	1.6	0	48
	(DME)	(H_2O_2)			
6	6.2	0	1.7	0	69
7	6.2	90	1.1	0.9	126
8	6.2	90	1.1	1.0	79

P_d: electrical discharge power
ΔP_c: chamber pressure achieved (gauge)
ΔT_{max}: increment of plume temperature

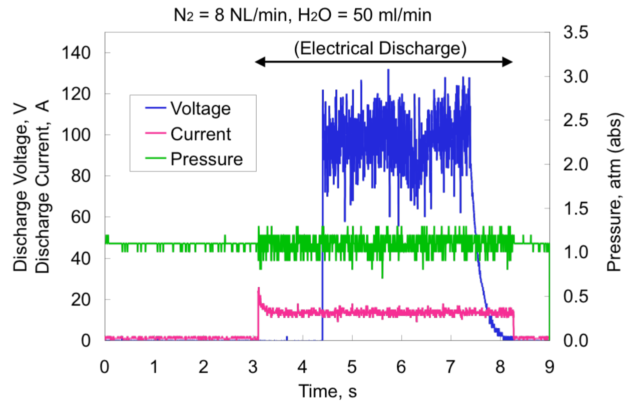

Figure 6. Discharge voltage, current and chamber pressure with N_2-H_2O thruster at the experimental No. 1 in Table 3. Discharge voltage began to be measured on the way of the discharge.

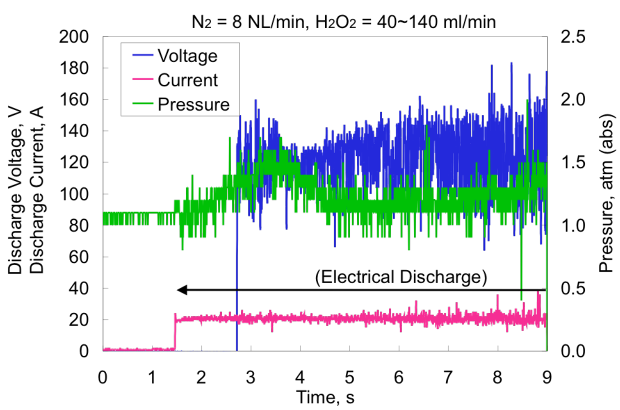

Figure 7. Discharge voltage, current and chamber pressure with N_2-H_2O_2 thruster at the experimental No. 4 in Table 3.

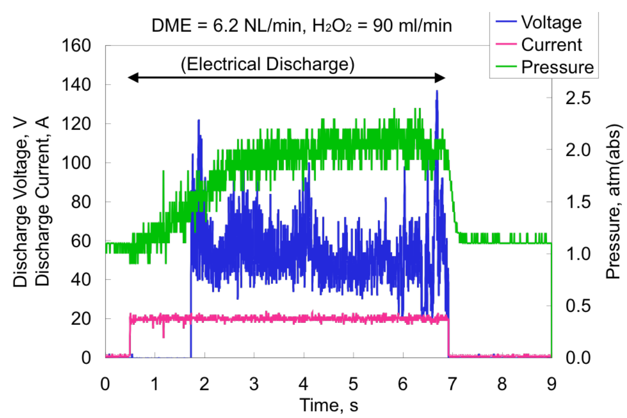

Figure 8. Discharge voltage, current and chamber pressure with DME-H_2O_2 thruster at the experimental No. 8 in Table 3.

B. Consideration of Thermal Energy Balance and Future Works

Although the discharge plasma affected to induce hydrogen peroxide decomposition, the amounts of pressure increment were lower than estimated. As an example, we consider a thermal energy balance for the experimental number 3 at Table 3. If 75 ml/min of 60 wt% hydrogen peroxide was decompose with 1.4 kW arc discharge, 2.5 kW of net enthalpy would obtained as shown in Fig. 9. On the other hands, when assuming that temperature in the reaction chamber is stably 33 K higher than room temperature, enthalpy of about 1.1 kW will be absorbed to the chamber wall. This means that most of enthalpy generated through the constrictor did not contribute to the thrust. Therefore, further thermal design will be required for more practical application.

Moreover electrical discharge power was much higher (~ 2 kW) than the target of PCT (~ 300 W). In order to reduce the discharge power consumption, higher concentration of hydrogen peroxide will be employed and stationary alternating current discharge will be evaluated as well as direct current discharge. In addition, enough volume of the plasma region for effective reaction should be secured even under high pressure. Then a PCT, which had resolved these ideas, will be worthwhile evaluating its thrust performances.

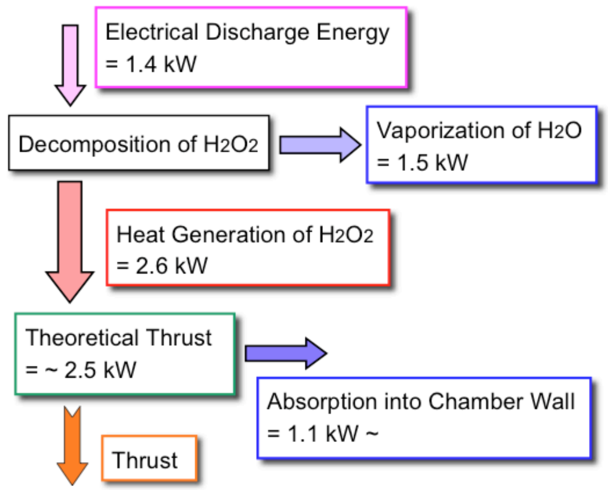

Figure 9. Thermal balance at the experimental No. 3, refer to Table 3.

V. Conclusions

Plasma chemical thruster, we suggested, is expected to remove solid catalyst and decompose a green propellant by electrical discharge plasma. With preliminary model of the PCT, the following results were indicated,

1) Decomposition of 60 wt% hydrogen peroxide of was confirmed with direct current arc discharge plasma. It is evaluated that the plasma chemical thruster is worthwhile developing for practical application.
2) Thrust improvement will be available when DME is applied as carrier gas.
3) Electrical discharge power was much higher than that for practical utilization. It is considered that higher concentration of hydrogen peroxide and other method of plasma production, for example stationary alternating current discharge, are effective to operate the PCT with lower electrical power consumption (less than 300 W).

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