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Development and Ground Tests of a 100-Millinewton Hydrogen Peroxide Monopropellant Microthruster

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A hydrogen peroxide microthruster for maneuvering the attitude of small satellites is developed by first studying the outstanding problems of the miniaturization of thruster systems, such as the enhanced heat loss and decomposition instabilities of bubbles in liquid. Theoretical analysis is employed to determine the test and design parameters of the hydrogen peroxide microthruster. The design concept of a 100-mN hydrogen peroxide microthruster is proposed, and the microthruster is demonstrated to perform a minimum impulse bit of 10^{-2} N · s, which can provide a microsatellite slew at a speed of 0.1 deg/s. The total volume of the microthruster prototype is about 0.9 cm^3, with a throat diameter of 0.5-mm packing, with silver flake as the catalyst, and 92% hydrogen peroxide is adopted with a flow rate of 0.18 g/s. Measurements of the ignition delay at different catalyst-bed preheating temperatures are compared to define the operating parameters for practical applications. Test results show that the hydrogen peroxide microthruster gives a good c^* efficiency and a short ignition delay compared with the performance of large-scale systems. Under atmospheric pressure at sea level, the developed microthruster can produce 182 mN with a specific impulse of 101 s.

Nomenclature

A_e	=	exit area
A_t	=	throat area
C_F	=	thrust coefficient
c^*	=	characteristic velocity
D	=	outer diameter of the catalyst-bed wall
h	=	convection coefficient
I_{sp}	=	specific impulse
k_a	=	conductivity of air
L	=	length of the catalyst bed
M_e	=	Mach number at exit
$\dot{m}$	=	mass flow rate
Nu_d	=	Nusselt number
P_e	=	nozzle exit pressure
Pr	=	Prandtl number
P_0	=	chamber pressure
Q	=	reaction heat
R	=	inner radius of the catalyst bed
Ra_d	=	Rayleigh number
S_c	=	remnant reaction heat
t_c	=	characteristic time
t_r	=	residence time
V_e	=	exit velocity
ΔH_{diff}	=	enthalpy difference between the inlet and outlet
ΔT	=	ΔT temperature difference between the wall and ambient temp
η_{c^*}	=	c^* efficiency
η_t	=	thermal efficiency
θ	=	contact angle
ρ	=	density of decomposition gas
ρ_l	=	hydrogen peroxide density in the liquid phase
σ_{lg}	=	surface tension of hydrogen peroxide on the solid surface

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I. Introduction

MICROTHRUSTERS are used for attitude control and orbit adjusting for microspacecraft, which are defined by the U.S. Air Force Research Laboratory to be of a weight less than 100 kg [1]. For maneuvering the attitude of the microspacecraft, the microthruster needs high resolution of the impulse bit. The impulse bit of a compatible microthruster would be less than 10^{-2} N · s to fit the mission demand. Monopropellant thruster possessing merits of high energy density, higher I_{sp} than a cold-gas system, and higher reliability make it a suitable candidate for microsatellites or microspacecraft. In recent years, high-test peroxide (HTP) has attracted renewed attention as a safer and environmentally friendly green monopropellant and become a potential alternative to the hazardous hydrazine propellant. Although the specific impulse of high-test peroxide is smaller than that of hydrazine, the advantages of easier and safer handling of hydrogen peroxide, resulting in cost and time savings in system testing and development, are worthwhile tradeoffs. To date, the thrust of off-shelf hydrogen peroxide monopropellant thrusters is usually in the range of tens of newtons. Hitt et al. [2] presented a prototype microelectromechanical system (MEMS)-based hydrogen peroxide microthruster constructed of silver catalytic pillars in the combustion chamber. Experimental results showed incomplete decomposition and poor thrust efficiency at the nozzle exit. It poses practical challenges for researchers in the miniaturization of hydrogen peroxide thrusters based on the past experience of large-scale thrusters. Some difficulties were encountered when reducing the size of a hydrogen peroxide

microthruster. The enhanced heat loss due to the significantly increased surface-to-volume ratio results in lower decomposition temperature and poor efficiency. The two-phase phenomenon of bubbles in liquid may also significantly affect the decomposition stability in the catalyst microchannel. The stabilizers in a miniaturized hydrogen peroxide system show more serious influence on the decomposition process than that of an ordinary hydrogen peroxide rocket. The intrinsic properties of the hydrogen peroxide decomposition phenomenon should be carefully examined in the design of a hydrogen peroxide microthruster. The objective of this study is to investigate the problems of miniaturization and to propose specific design concepts for a hydrogen peroxide microthruster to fit the requirements of the attitude control system of microsatellites with acceptable performance and the thrust on the order of hundreds of millinewtons.

II. Difficulties of Hydrogen Peroxide Microthrusters

In the development of a hydrogen peroxide microthruster, specific practical difficulties are encountered and have to be overcome by special design and operation considerations. It has been shown [2] that one of the major problems in a MEMS-based hydrogen peroxide microthruster is the inhibition of decomposition progress due to enhanced heat loss as the surface-to-volume ratio is increased in miniaturization. In addition, gas bubbles are usually observed in the microchannel, and effects of impeding fresh hydrogen peroxide from contacting the catalyst surface become relatively significant as the size is reduced. Cheung and Tilston [3] demonstrated that in a hydrogen peroxide bipropellant system for micro air vehicles, enhanced heat loss in small engines resulted in a low chamber temperature, 768 K in their tests, and a specific insulation layer of the engine was needed. Osaki and Takahashi [4] investigated the decomposition phenomena of hydrogen peroxide in a catalytic microchannel and found that the decomposition gas stuck on the catalyst surface, and bubbles in the liquid affected flow rate measurements and the catalytic decomposition process. A resistant heater was used to promote catalytic decomposition, and hydrophobic surfaces were proposed to improve the two-phase problem in the hydrogen peroxide microthruster.

The scaling issues on the performance and combustion [5,6] of a microthruster, as well as of a power generation system, have been some of the primary problems and concerns in the process of downsizing and miniaturization. A simple scaling analysis can show that the enhanced heat loss of small/micro systems is related to the surface-to-volume ratio, which is proportional to the inverse of the characteristic length L^{-1}. This implies that the ratio of heat loss to heat generation will significantly increase as the size decreases. It is inevitable for a microthruster to operate at a low temperature and a low thermal efficiency. However, for hydrogen peroxide microthrusters, the scaling consideration is slightly different, because the hydrogen peroxide is decomposed on the catalyst surface and in the volume, due to homogeneous thermal decomposition. It seems that the increased surface-to-volume ratio in microthruster design may benefit the surface reaction of the catalyst. Yet, in reality, with fixed catalyst cell size, the catalyst surface-to-volume ratio remains the same when reducing the chamber size. In other words, the specific heat generation per unit of hydrogen peroxide by catalytic surface reaction remains the same, but the heat loss is enhanced as the size of the hydrogen peroxide microthruster is reduced. This would pose an outstanding limitation on the design of a catalytic hydrogen peroxide microthruster.

Furthermore, hydrogen peroxide is a strong oxidizer and actively decomposes into superheated steam and oxygen. The sudden burst of the decomposition process on the catalyst, immediately producing a large volume of high-temperature oxidizing gas, could easily scrape off the catalyst and disintegrate the microstructure from the high-surface-area material such as silica or alumina. The selection of durable catalyst and associated substrate is an important issue in the design of a hydrogen peroxide microthruster. Pure silver or plated silver on a nickel screen would be ideal as a practical choice. In practice, with lower chamber temperature, the catalyst bed in the microthruster system may not be as active as that in the hundreds-of-newtons hydrogen peroxide rockets. According to Satterfield [7], either catalytic decomposition or the vapor-phase homogeneous decomposition process depends strongly on the reaction temperature and homogeneous decomposition (also called thermal decomposition) subsequently dominating the reaction after 450°C. It suggests that for a fair thrust efficiency and quick reaction (sufficiently short ignition delay) of a microthruster, the chamber temperature must be raised high enough to support vapor-phase decomposition and a homogeneous reaction. As a result, external resistant heating may be required to initiate the violent reaction from the initial cold condition for a hydrogen peroxide microthruster [8]. Moreover, long-term operation at low temperatures of a hydrogen peroxide microthruster due to heat loss may promote catalyst aging. It will significantly reduce the activity of the catalyst, especially for silver catalysts.

A. Size Limit of an Operational Hydrogen Peroxide Catalyst Bed for a Microthruster

As discussed already, many problems and difficulties of a hydrogen peroxide microthruster can be related to the size, in terms of the surface-to-volume ratio, of the microthruster. In the design of an operational hydrogen peroxide microthruster, the size limit must first be analyzed and discussed. For a high-temperature chemical reactor such as a hydrogen peroxide catalyst bed, there exists a minimum operational size of the catalyst bed. The size limit is based on the proper balance between the reaction rate and heat loss rate of the system to the surroundings. In other words, for an operational hydrogen peroxide microthruster, the chamber temperature determined by the balance between the reaction and heat loss rates must be maintained sufficiently high during the operation to produce acceptable thrust and thermal efficiencies (hence, to achieve a quick response for the mission). Therefore, one can evaluate the size limitation of the catalyst bed by considering the energy balance with some justified simplification assumptions. In the analysis, we assume the catalyst bed to be porous like the packed silver bed and cylindrical in geometry. Reheating (such as the counterflow channel, which could recirculate the reaction heat to increase the overall efficiency) will not be considered, because for a propulsion system, especially involving a vaporization process such as hydrogen peroxide, it is unfavorable with complex channels, which may result in decomposition instability. The decomposition instability in a small catalyst channel of a hydrogen peroxide system will be discussed in the next section. Figure 1 shows the schematic diagram of the analysis. Hydrogen peroxide enters the porous catalyst with a uniform velocity profile and decomposes into oxygen and steam accompanied by reaction heat release. The heat is carried out of the catalyst bed by the main stream and is dissipated radially to the environment through the wall. The energy balance can be expressed as follows:

$$\dot{m}Q = \pi DLh\Delta T + \dot{m}\Delta H_{\text{diff}} \tag{1}$$

Because the study focuses on ground tests, the heat is lost to the environment primarily by convection. However, in space, the radial

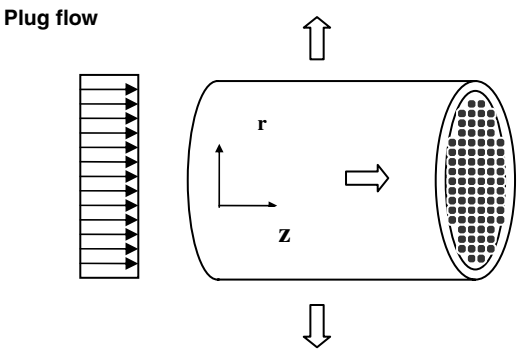

Fig. 1 Schematic diagram of the size-limit analysis.

heat loss is due to radiation. Because the decomposition temperature for hydrogen peroxide does not exceed 1300 K, the thermal radiation effect is not obvious. The left side of Eq. (1) is the energy generation by decomposition, where Q is the reaction heat and $\dot{m}$ is the mass flow rate of hydrogen peroxide. The first part on the right side of the equation is the heat loss to the environment, where πDL is the outer-wall surface area of the catalyst reactor, h is the convection coefficient, and ΔT is the temperature difference between the wall and the environment. The second part is the enthalpy convected by the stream. For a hydrogen peroxide microthruster to produce an acceptable thrust level and impulse in the least conditions, the system must overcome the so-called latent-heat barrier. This is when the temperature exceeds the boiling point of hydrogen peroxide at about 150°C, operating in the gas-phase decomposition process for a self-sustained decomposition, because the reaction rate in the liquid phase is relatively very slow. The boiling point could be considered as a threshold temperature for a practical hydrogen peroxide microthruster. So in the analysis, we assume the catalyst-bed temperature to be 150°C. If we subtract the left side from the second term of the right side of Eq. (1), then the result is the remnant chemical reaction heat that is used for heat loss and for self-promotion of decomposition reaction. The heat loss to environment must be less than the remnant heat so that the gas-decomposition process can be promoted and accelerated in the catalyst bed. Equation (1) can be rewritten as

$$\pi Nu_d k_a L \Delta T \leq \dot{m} S_c \tag{2}$$

The left side of Eq. (2) is the heat loss to the environment near the outer wall of the catalyst bed and it must be less than $\dot{m}S_c$, the remnant chemical energy of hydrogen peroxide. The mass flow rate $\dot{m}$ could be expressed by the liquid-phase residence time of hydrogen peroxide, t_r, channel length L, and inner diameter r. We assume that the residence time is equal to the characteristic reaction time t_c of this catalyst bed. The characteristic time is defined as the time that the decomposition process can complete in a specific catalyst bed. It represents the global activity of a specific catalyst bed. Equation (2) could then be expressed as follows:

$$\pi Nu_d k_a L \Delta T \leq \rho \pi r^2 \frac{L}{t_c} S_c \tag{3}$$

For meso- and microthrusters, the catalyst-bed size may be as small as 1 cm^3, and the Biot number of this dimension will be less than one, which suggests that the outer-wall temperature may be close to the temperature of the inner wall, which is assumed to be 150°C in the limiting case. Hence, the temperature difference ΔT is estimated to be about 100 K. The Nusselt number Nu_d of free convection to the environment can be evaluated by using the experimental formula of a horizontal constant temperature cylindrical tube, proposed by Churchill [9]:

$$Nu_D = \left\{ 0.6 + \frac{0.387 Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}} \right\}^2 \tag{4}$$

The resultant Nu_d is about 1.17. Substituting the following parameters

$$S_c = 0.43 \times 2887 \text{ kJ/kg} \qquad k_a = 0.033 \text{ W/m} \cdot \text{K}$$
$$\rho = 1.4 \text{ g/cm}^3 \qquad Nu_D \cong 1.17$$

into Eq. (3), then the relationship of inner diameter and characteristic time is expressed as

$$d \geq 9.316 \times 10^{-5} t_c^{1/2} \tag{5}$$

and plotted in Fig. 2. The curve in this diagram represents that there is a relative minimum catalyst diameter for a specific catalyst bed (characteristic time), and the assumption that the residence time is equal to the characteristic time promises the best decomposition efficiency. For example, the size and condition of the MEMS microthruster proposed by Hitt et al. [2] is found to locate almost on the curve in Fig. 2. This implies that the system will not be able to overcome the latent-heat barrier and the radial heat loss to step into gas-phase decomposition to deliver reasonable thrust. In other words, the decomposition temperature at the exit for the catalyst bed in the left-side region of this curve will never be higher than 150°C in any mass flow rate. This figure also shows that for MEMS hydrogen peroxide microthrusters, as the size is decreased, the allowable characteristic time margin is significantly reduced and the system becomes impractical, especially for sizes smaller than 100 μm. On the contrary, for the existing few tens-of-newtons hydrogen peroxide rockets, the liquid-phase residence time during the ignition process is about 0.5 s, meaning that the latent-heat barrier is not important. In practice, a catalyst bed with a size smaller than 1 mm in diameter yielding unacceptable efficiency [2] is impractical; thus, this dimension may also induce another severe "bubble-instability" problem. As a result, a catalyst bed of several millimeters in diameter will be used to design the microthruster in this research to alleviate the heat loss problem and other difficulties.

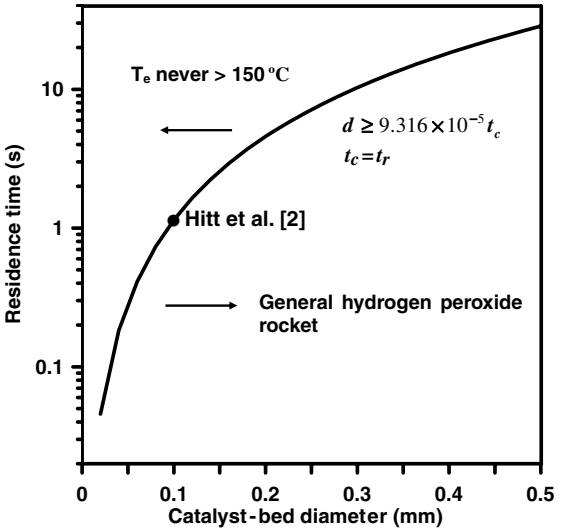

Fig. 2 Relation between minimum diameter and residence time.

B. Two-Phase Phenomenon in Catalyst Channels

The two-phase problem of gas bubbles in liquid frequently occurs in the connecting tubes and catalytic microchannels [2,4]. The decomposition gas bubbles stick to the tube walls and catalyst surface and obstruct the flow and reaction. If the catalytic channel is heated higher than 200°C, hydrogen peroxide gasifies rapidly to form bubbles in the channel and blocks the flowfield. The bubble will stay and grow in the channel till its breakdown, and a new bubble grows and brings new obstruction. This bubbling cycle repeats and results in decomposition instability. The problem can be analyzed from the balance of surface tension and inertial force. The surface-tension force between the gas bubble and solid boundary is given by

$$F_s = \sigma_{1g} 2\pi r_e \cos\theta \tag{6}$$

where σ_{1g} is the surface tension between hydrogen peroxide and the specific catalyst surface, r_e is the radius of the bubble contact edge, and θ is contact angle. The inertial force exerting on the bubble is given by

$$F_i \propto \rho V^2 \pi r_b^2 \tag{7}$$

where ρ is the density of hydrogen peroxide, V is the flow velocity, and r_b is the radius of the bubble. In a microchannel, it is reasonable to take r_e and r_b to be of the same order. So the ratio of surface tension to inertial force could be represented as follows:

$$\frac{\text{surface tension}}{\text{inertial force}} \propto \frac{2\pi r \sigma_{1g} \cos\theta}{\rho V^2 \pi r^2} \propto r^{-1} V^{-2} \tag{8}$$

This equation shows that the smaller the channel size, the higher the ratio, implying favorable bubble formation. In addition, for complete decomposition in the catalytic channel, longer residence time (lower flow velocity) is preferred, and this unfavorable design would lead to more serious bubble-lock phenomenon in a hydrogen peroxide microthruster. Past experience shows that a catalyst bed with a diameter larger than 1 mm may alleviate this problem.

For safety reasons, stabilizers such as sodium pyrophosphate are usually added to hydrogen peroxide. The catalyst activity may significantly degrade as the concentration of stabilizers increases. In rockets using hydrogen peroxide, inhibition of the stabilizer may not be so significant, because the reaction temperature is a near-adiabatic decomposition temperature, for which the thermal decomposition is dominant in the process. On the contrary, for hydrogen peroxide microthrusters, the reaction temperature is lower and stabilizers may pose a serious influence on the catalytic decomposition process.

In view of the preceding discussions and arguments of size-limitation and bubble-blockage problems, it is not advisable to reduce the size of the catalyst bed smaller than 1 mm for an operational hydrogen peroxide microthruster. Therefore, in this study, for fair compromise between performance and size, we finally decided to develop a 5-mm hydrogen peroxide microthruster with significant thrust and thermal efficiencies. This is suitable for generating a 100-mN level of thrust with a minimum impulse bit of 10^{-2} N · s. It can provide the slew at a speed of 0.1 deg/s for a 50-kg satellite.

III. Catalyst Selection

The catalysts for hydrogen peroxide can be divided into homogeneous catalysts and heterogeneous catalysts. Homogeneous catalysts such as solutions containing Fe^{2+}, Fe^{3+}, Mn^{n+}, or Cu^{2+} perform relatively more violent catalytic reactions than heterogeneous catalysts. However, the consumption of catalyst-demanding additional tanks, pipes, and fittings leads to the adverse miniaturization of the homogeneous-catalyst system. Conventionally, hydrogen peroxide rocket motors use silver screen or nickel screen plating with silver as catalysts. So far, silver screen is still the preferred choice. The surface area of silver plated on the nickel screen could be controlled by varying current density in the electroplating process. Consequently, by comparing the silver screen and nickel screen plated with silver, the former shows better durability for long periods of service and the latter possesses a shorter ignition delay. For better reactive decomposition, samarium nitrate has been proposed to promote the activity of silver screen [10,11]. It not only serves as the solution of passive treatment for the contact surface with hydrogen peroxide, but nitric acid is also used to activate a new silver surface [12]. Different conclusions on the role of samarium nitrate or nitric acid in the hydrogen peroxide decomposition process have been reported in the literature. Nevertheless, the oxidation of the silver surface would be the most common explanation [12,13].

Considering the durability and activity, silver is selected as the catalyst of the hydrogen peroxide microthruster in this study. First, a γ-Al_2O_3 coating with silver in the shape of pellets and a pure silver pellet with a 1-mm diameter are both tested. The former cannot operate for a long time because the silver will be washed out by hydrogen peroxide. The latter has poor performance because the outlet temperature does not exceed 250°C. Finally, pure silver flake sized between 90 and 250 μm is adopted, which is easy to fill and fabricate. It also has the best performance among these catalyst types. In the microthruster, the catalyst chamber filled up with silver flakes and a fine stainless steel screen is used as the baffle. This screen is also used to uniformly distribute hydrogen peroxide. The total mass of silver flakes is about 0.7 g.

IV. Thruster Design

Major operating parameters such as the hydrogen peroxide flow rate, throat, and exit areas of the nozzle are estimated and determined by theoretical analysis with suitable assumptions [14]. These include steady-state isentropic flow between the catalyst bed and outlet, ideal gases, all products in the gas phase, neglecting friction and boundary effects before the throat, exhaust gases leaving the nozzle in the axial direction, and chemical equilibrium. The known conditions are the thrust of 100 mN and ambient pressure of 101.3 kPa, and the unknown parameters are the hydrogen peroxide flow rate, reactor pressure, reactor temperature, throat area, and nozzle outlet area. If the exit pressure expands to the ambient pressure, it will produce the highest thrust output, defined as

$$F = \dot{m}V_e = \left\{\left[1 - \left(\frac{P_e}{P_o}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]\frac{2\gamma}{\gamma-1}RT_0\right\}^{\frac{1}{2}} \tag{9}$$

Here, we need to presume the catalyst chamber pressure P_0 and temperature T_0 to evaluate the exit velocity V_e. From Eq. (9), the mass flow rate can be calculated. Then the throat area will be obtained from Eq. (10):

$$\frac{\dot{m}}{A_t} = \sqrt{\frac{\gamma}{RT_0}}P_0\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \tag{10}$$

The overall volume of the microthruster in the study is about 1 cm^3. From preliminary experiments, the catalyst chamber temperature of the 92% hydrogen peroxide may reach nearly 800 K. The chamber pressure would refer to Platt's [15] design of a hydrazine thruster for a 10-kg nanosatellite for which the catalyst chamber pressure is assumed to be 750 kN/m^2. Using 800 K and 750 kN/m^2 as the reference catalyst chamber temperature and pressure, we can obtain the exit Mach number of 1.93 and the exit temperature of 538 K from the isentropic relation.

The exit velocity can be obtained from the exit Mach number and the exit temperature. Then the mass flow rate of 92% hydrogen peroxide, which is 0.10 g/s, is calculated from Eq. (9). The calculated throat area A_t is 1.59×10^{-7} m^2 and the corresponding diameter D_t is about 0.45 mm from Eq. (10). The exit diameter of the thruster can be estimated by Eq. (11):

$$\frac{A_e}{A_t} = \left(\frac{2}{\gamma+1}\right)^{\left[\frac{\gamma+1}{2(\gamma-1)}\right]} \Bigg/ \sqrt{\left\{\frac{2}{\gamma-1}\left[\left(\frac{P_e}{P_o}\right)^{\frac{2}{\gamma}} - \left(\frac{P_e}{P_o}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}} \tag{11}$$

According to the pressure ratio between the exit and chamber, the exit area is 1.69 times A_t and the corresponding outlet diameter is 0.59 mm. For convenience in fabrication, the throat diameter of nozzle is adjusted to be 0.5 mm, with an expansion angle 15 deg to the exit diameter of 0.7 mm, and the flow rate is adjusted to be 0.18 g/s.

The performance of the catalyst chamber and the thruster is usually evaluated based on critical parameters such as characteristic velocity c^*, c^* efficiency η_{c^*}, thermal efficiency η_t, thrust coefficient C_F, and specific impulse I_{sp}. These parameters are defined in the following equations:

$$c^* \equiv \frac{A_t P_o}{\dot{m}} \tag{12}$$

$$C_F \equiv \frac{F}{A_t P_o} \tag{13}$$

$$I_{sp} = F/\dot{m}g \tag{14}$$

V. Experiment

A. Experimental Setup

The experimental setup in this study is described as follows. Hydrogen peroxide is stored in a pure aluminum tank and pressurized by the 1.4×10^6 N/m^2 nitrogen bottle. The flow rate is controlled by a high-precision microneedle valve. We use a normal-off solenoid

valve to control the thruster operation. In this study, we investigate the ignition delay time of the microthruster in different preheating temperatures. In the ignition delay tests, the tests are initiated by activating the solenoid valve when the catalyst bed reaches a prescribed temperature when the external power is off. Temperature and pressure are measured downstream of the catalyst bed. The SSI Technology pressure transducer (P51-25BarS-A-MD-20ma) is used, which can measure up to 363 psi with superior accuracy of ±0.5%. From the chamber pressure, the characteristic velocity can be calculated and the decomposition efficiency can be estimated. A 75-μm K-type thermocouple with the error limit of 2.2°C is used in the chamber to avoid additional catalytic reaction on its junction. The materials for pipes and valves are stainless steel 316, and the O-ring used in the microthruster system is made by Viton.

B. Thruster Operation Parameters

The prototype of the microthruster is designed to generate a thrust on the order of 100 mN. According to previous studies [16], for a 100-mN thrust, a mass flux of 100 $kg/m^2 \cdot s$ is usually quoted. However, it should be noticed that the thrust of these studies ranges from tens to thousands of newtons. The mass flux was determined in steady-high-temperature operation. However, for a miniature design in which large heat loss is prevalent, the cross-sectional diameter of the 100-mN microthruster calculated from the mass flux of large thrust engines would be 1 to 2 mm. It may be too small to sustain acceptable performance and may effectively lead to the decomposition instability in such a small chamber. In this study, a catalyst-bed diameter of 5 mm is used. Furthermore, the ignition process must be considered to evaluate the suitable catalyst volume. For low-temperature ignition, the decomposition process may remain at the boiling temperature of hydrogen peroxide for seconds. As a result, using the residence time of liquid-phase hydrogen peroxide to estimate the chamber length is practical. The liquid-phase residence time of hydrogen peroxide used in Willis's study [12] is about 0.38 s, and 0.4 s is adopted in this study. The calculated length of the catalyst chamber is 5.5 mm. The packed weight of the silver catalyst is 0.6 g. The overall hydrogen peroxide microthruster, including the distribution plate, catalyst chamber, and nozzle, weighs 5.8 g in total. The design of the hydrogen peroxide microthruster is shown in Fig. 3, and the hydrogen peroxide microthruster parameters are listed in Table 1.

C. Thrust Stand

To accurately measure the thrust, a precision thrust stand accurate to millinewtons is designed to measure the thrust under the atmospheric pressure. Figure 4 shows the thrust stand. Because the thruster produces just hundreds of millinewtons, the influences of flexible connecting tubes and solenoid wire could be significant in the thrust measurements. To reduce these influences, the flow and microthruster systems are mounted on the suspending plate. The thrust is measured from the deflection of a calibrated thin copper foil with four strain gauges connecting the centerline of the plate and an adjustable stage. The strain gauges (KYOWA type KFG-20-120-C111L1M2R) have a gap factor 2.09 and the resistance is 120.4Ω. The Wheatstone bridge formed by the stain gauges is initially nullified and then connected to an amplifier and a 50-Hz low-pass filter. Subsequently, the voltage signals output from the circuit are digitized by an A/D converter and transferred to the actual thrust of the microthruster. Details of the thrust calibration follow the method developed by Stephen et al. [17]. In situ thrust calibration is carried out before every thrust test using standard weights. By changing the mass of the standard weight, the different output voltage is recorded. The relation between output voltage and thrust is shown in Fig. 5. Ten data points for voltage were taken at a particular weight in Fig. 5 and the error bars are also shown. The standard deviations of output voltage are very small. For example, the standard deviation is 0.109 mV for the average of 66.175 mV, and it is 0.022 mV for the average of 7.71 mV. The calibration ranges from 2 to 490 mN, and the thrust stand can analyze a variation of 1 mN. It almost has a linear relationship between voltage and force, and the calibration factor can be determined from the slope of the calibration curve.

Table 1 Hydrogen peroxide microthruster properties

Dimension	$\varphi 8 \times 13$ mm
Hydrogen peroxide flow rate	0.18 g/s
Throat diameter	0.5 mm
Exit diameter	0.7 mm
Expansion angle	15 deg
Structure material	SS316
Seal material	Viton
Total weight	5.8 g
Catalyst	0.7 g, 99.9% silver
Catalyst property	Flake between 90 and 250 μm
Packed volume	120 mm^3
Porosity	0.56

VI. Results and Discussion

A. Decomposition Characteristics of Hydrogen Peroxide

In Figs. 6 and 7, the time trace of the chamber temperature and pressure for the cases of preheating temperatures of 300 and 423 K, respectively, are shown. The catalyst is resistively heated with a power between 10–15 W. Once the catalyst attains the destined preheating temperature, the valve will open and the external power will be switched off immediately. Without preheating the catalyst bed, the hydrogen peroxide microthruster requires about 15 s to reach the steady-state pressure of 565 kN/m^2 after the solenoid valve is opened. The reactor temperature rapidly reaches 420 K after the valve opens and stays at 420 K for about 12 s. It then sharply increases to 900 K and drops a little to the steady state, at approximately 820 K. When the catalyst bed is preheated to 423 K, the pressure rises to 689 kN/m^2 in 50 ms after the valve is opened, whereas the catalyst-bed temperature increases to about 850 K in 1 s. Moreover, it decreases slightly to the steady-state pressure of 579 kN/m^2 and temperature of 840 K.

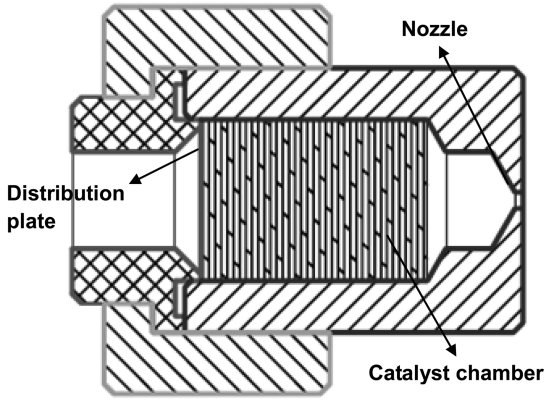

Fig. 3 Design of hydrogen peroxide microthruster.

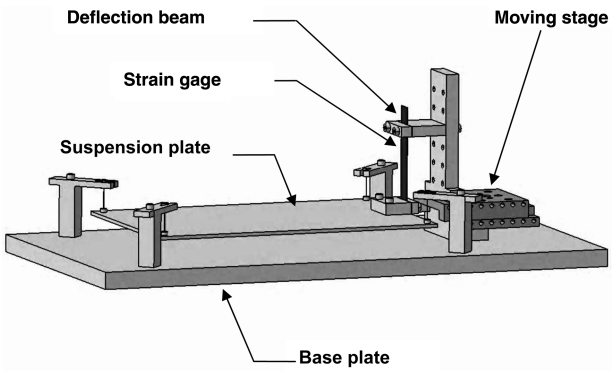

Fig. 4 Thrust stand.

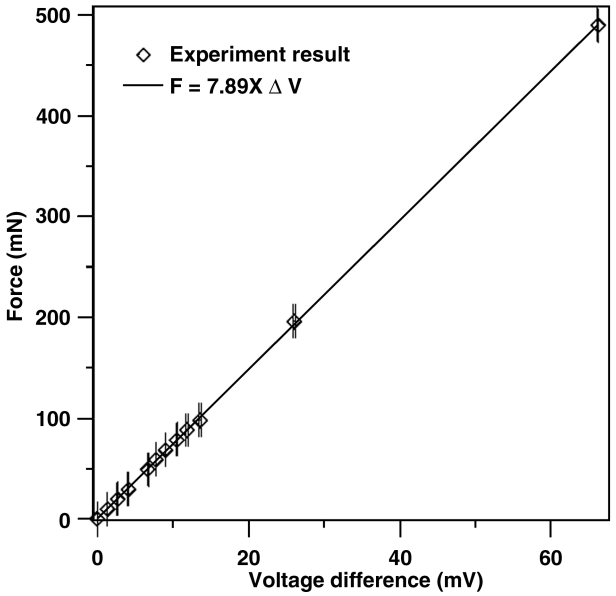

Fig. 5 Thrust-stand calibration.

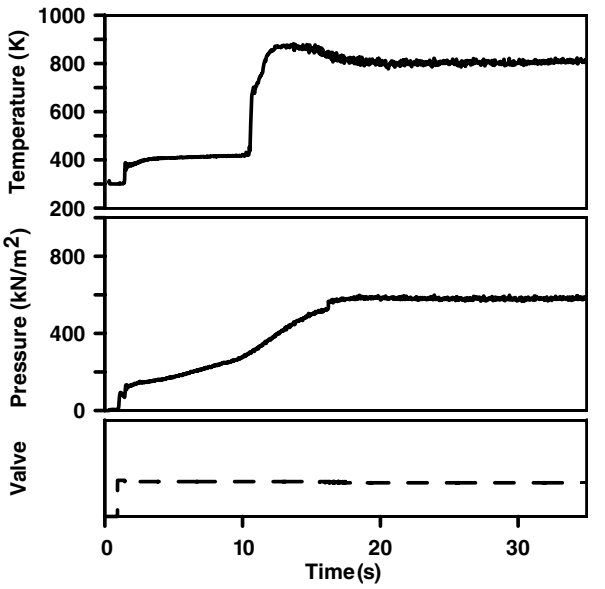

Fig. 6 Decomposition temperature and pressure vs time; catalyst-bed preheating temperature 300 K.

During the ignition process, it is obvious that the catalyst-bed temperature will stay at 420 K for seconds if the catalyst chamber is not preheated or the preheating temperature is low. The delay time can be reduced when the preheating temperature increases. The boiling point of hydrogen peroxide is about 423 K. After 423 K, liquid hydrogen peroxide is vaporized and the decomposition reaction is enhanced by vapor-phase thermal decomposition. Therefore, the boiling point of hydrogen peroxide can be regarded as a precursor of the hydrogen peroxide microthruster, leading to rapid reaction and generating useful impulse bits in practice. For serving as a rapid-response and high-efficiency attitude control system, methods of enhancing the catalyst decomposition process are used to overcome the latent heat. This leads to global thermal decomposition, which is required for the hydrogen peroxide microthruster.

B. Performance of the Hydrogen Peroxide Microthruster

The thrust performance with different preheating temperatures is shown in Table 2. The temperature and pressure are the average value of steady state. The steady chamber pressure is in the range of 550 to 600 kN/m^2 for most test cases. The maximum c^* efficiency is about 0.93. This value is smaller than that of the hundreds-of-newtons hydrogen peroxide rocket, which may reach well above 95% in c^* efficiency. The average reactor temperature is 829 K and the corresponding thermal efficiency is about 70%. Miniaturization in thruster size has obvious effects on the microthruster performance in terms of chamber temperature, pressure, and efficiencies.

A thruster for attitude control of microspacecraft, the ignition delay time, is an important index of thruster performance. In this study, the ignition delay time is defined as the time required to attain 95% steady pressure after the valve is opened. Note that the response time of the solenoid valve, which is estimated to be 6 to 20 ms, is included in the ignition delay. The ignition delay time is about 14 s without preheating, which is not suitable for the requirement of attitude control. Tests with different preheating temperatures are performed and the results are shown in Fig. 8. For preheating in the temperature range between 323 and 363 K, the ignition delay times are more than 10 s. With the preheating temperature increased to 403 K, the ignition delay time may be reduced to 150 ms, further to 50 ms at 423 K, and 35 ms at 453 K. As mentioned already, liquid hydrogen peroxide has to be vaporized before proceeding to rapid vapor-phase decomposition. Therefore, a preheating temperature above 420 K for a practical hydrogen peroxide microthruster is needed for quick response. The microthruster usually has a small heat capacity and, practically, it is not difficult to preheat to the 400- to 420-K range.

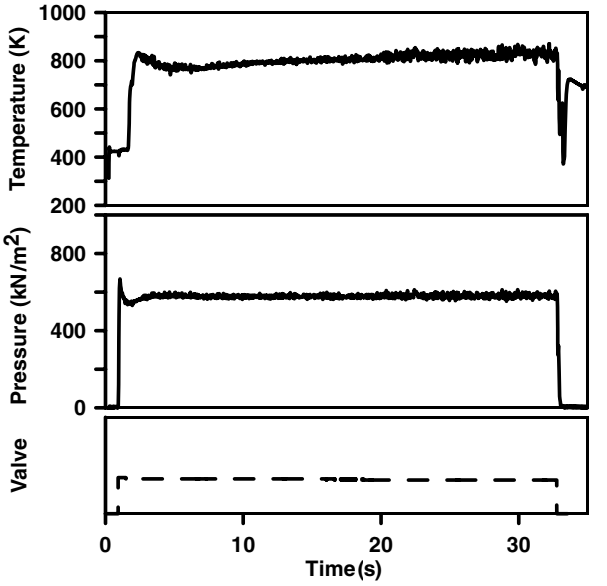

Fig. 7 Decomposition temperature and pressure vs time; catalyst-bed preheating temperature 423 K.

C. Durability

To coincide with the thruster duty cycle in a typical microsatellite mission, a total of 20 tests are performed to investigate the catalyst durability of the hydrogen peroxide microthruster. Unlike the rocket propulsion system, the micropropulsion system is mainly used for altitude control. In the operation of a micropropulsion system, being limited by the propellant tank and propellant mass, the firing duration is usually less than 12 s for most altitude control commands. Therefore, in the study, each test lasts continuously for 30 s. The total run time for catalyst durability is 600 s. In the experiment of [16], a throughput of 200 lbm of hydrogen peroxide was tested and performance degradation was observed to start at approximately 400 s. Therefore, it is worthwhile to test catalyst durability for longer than 400 s. Moreover, after 20 continuous cycles, the catalyst activity does not significantly reduce. It reaches a steady state with chamber pressure of about 572 kN/m^2 and temperature of more than 800 K. The c^* efficiencies calculated by the average pressure for these 20 tests is illustrated in Fig. 9. It shows that during the tests, the c^* efficiency constantly reaches around 90% with no obvious decay.

Table 2 Performance at different preheating temperature

Case	Temperature, K	Pressure, 10^5 N/m^2	Ignition delay, s	η_{c^*}	η_t
300 K	785.1	5.65	15.378	0.89	0.64
323 K	774.3	5.80	13.440	0.91	0.63
343 K	825.8	5.77	11.227	0.91	0.70
363 K	852.7	5.59	10.157	0.88	0.73
373 K	864.3	5.66	9.731	0.89	0.75
383 K	868.8	5.93	9.246	0.93	0.75
393 K	847.7	5.53	8.010	0.88	0.72
403 K	833.0	6.01	0.160	0.94	0.71
413 K	860.5	5.50	0.100	0.87	0.74
423 K	809.5	5.79	0.055	0.91	0.67
433 K	856.0	5.48	0.040	0.87	0.74
443 K	807.9	5.55	0.035	0.88	0.67
453 K	815.0	5.59	0.035	0.88	0.68

The average c^* efficiency of the 20 tests is 0.89, with the standard deviation of 0.028. The average thermal efficiency of the 20 tests is 0.69, with the standard deviation of 0.042. Several researchers proposed that the aging of silver is caused by the formation of silver oxide or coating of the hydrogen peroxide stabilizer on the surface of silver. The role of silver oxide in the catalytic decomposition of hydrogen peroxide is still debatable. Both promoting and prohibiting the decomposition process were proposed in the literature. Nevertheless, silver oxide is unstable and will reduce to silver above 160°C. For most hydrogen peroxide microthrusters, the working temperature is higher than 850 K, which is near the melting point of silver. We find that the silver flake becomes pale in color after testing, unlike the shining silver before using it. It may suggest that the silver surface becomes rougher with increased surface area after tests. Interestingly, the used silver bed seems to have a slightly higher performance than fresh silver.

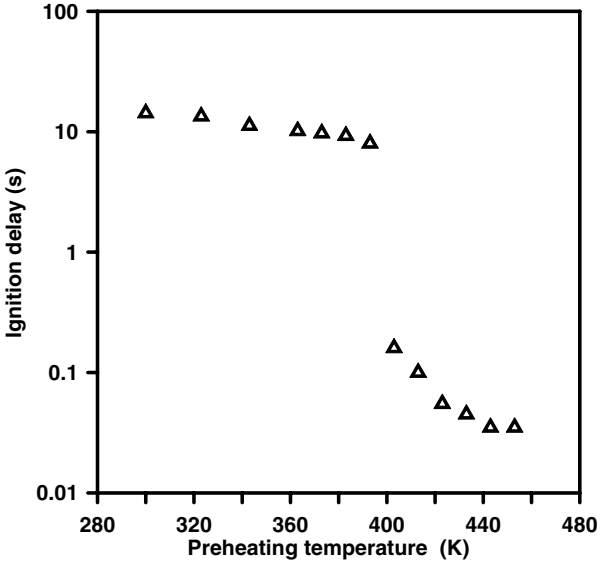

Fig. 8 Thrust test of hydrogen peroxide microthruster at ambient pressure with different preheating temperatures.

D. Thrust Measurement

In this study, thrust is measured by a thrust stand in terms of the deflection of a piece of copper foil. Previous tests of ignition delay show that a delay of less than 50 ms can be achieved at a preheating temperature of 420 K. We use this preheating temperature as the condition of the hydrogen peroxide microthruster for thrust measurement. Under the ambient pressure and temperature, according to the calibration factor in Fig. 5, the hydrogen peroxide microthruster can produce an average thrust of 182 mN, with the standard deviation of 7.8 mN. Figure 10 shows the time trace of thrust. The solenoid valve is opened at 500 ms and shut down after 10 s from the start of the test. The thrust at 530 ms has reached 300 mN and then descends to a steady thrust of 180 mN. By dividing data for the throat area and chamber pressure, a thrust coefficient ($C_F = 1.15$) of the microthruster can be obtained. A specific impulse of 101 s is achieved under the atmospheric pressure in the laboratory test using 0.18 g/s of 92% hydrogen peroxide. For space

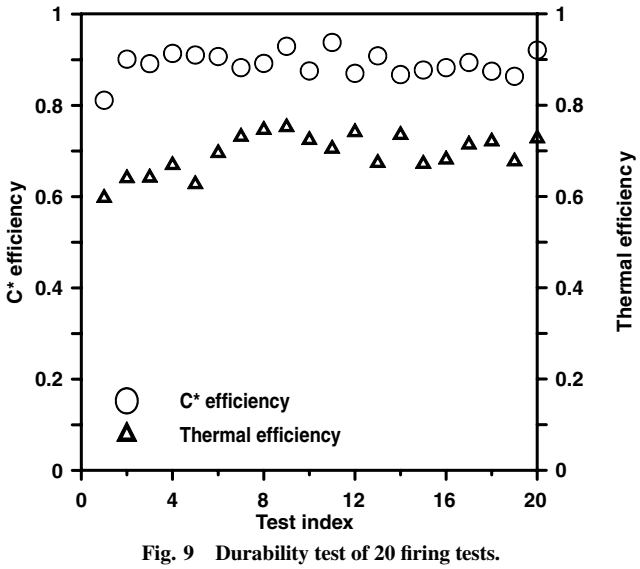

Fig. 9 Durability test of 20 firing tests.

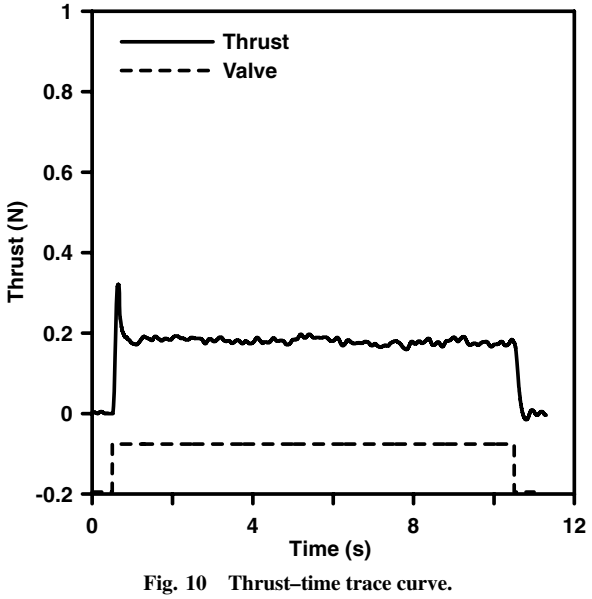

Fig. 10 Thrust–time trace curve.

applications, the thrust measurements in vacuum conditions are essential. However, the detailed analysis and discussion of vacuum tests will be the subject of future research. In this study, an estimated thrust for vacuum conditions is calculated based on the exit temperature and pressure of ground tests. A value of 221 mN is obtained from 182 mN, adding the product of exit pressure and exit area. It corresponds to a specific impulse of 125 s. In the space environment, because the heat convection is absent, a better performance of this microthruster can be anticipated.

VII. Conclusions

A prototype of a 100-mN hydrogen peroxide microthruster is developed to serve as the attitude control system for microspacecraft, and ground tests are performed. The outstanding problems of enhanced heat loss and decomposition instabilities of bubbles in liquid associated with the miniaturization of the hydrogen peroxide microthruster are studied. Theoretical analysis is employed to determine the test and design parameters of the hydrogen peroxide microthruster. The prototype of the hydrogen peroxide microthruster is packed with a 0.7-g catalyst bed of silver flake, and the overall thruster weighs just 5.8 g.

To improve the incomplete decomposition and to shorten the ignition delay time, the catalyst bed is preheated up to 453 K and demonstrated to overcome these difficulties in a limiting size of hydrogen peroxide microthruster. Test results show that more than 90% c^* efficiency can be achieved with 92% hydrogen peroxide at a flow rate of 0.18 g/s. Atmospheric ground test results show that the hydrogen peroxide microthruster generates 182 mN under atmospheric pressure, with a specific impulse bit of 101 s.

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