Catalyst Reactor Bed of Hydrogen Peroxide Decomposition for Upper Stage Motion Control

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Keywords: Thruster, Hydrogen peroxide, Catalyst

Abstract

A 50 N monopropellant thruster being developed for attitude control in a variety of aerospace application systems is described in this paper. Ninety percent hydrogen peroxide was selected as a propellant, since it is much less hazardous than hydrazine. A scaled down thruster with aluminum oxide loaded with the platinum in the reaction chamber was tested to determine propellant decomposition onto a catalyst. A scaled up 50 N thruster, with a catalyst bed of 3 cm in diameter and 4 cm in length, was evaluated by decomposition efficiency based on temperature, η_T, efficiency of characteristic velocity, η_{C^*}, and measurement of thrust. The performance of a 50 N thruster was 40.5 Newton in thrust, about 100 % in η_T, and 98 % in η_{C^*}, and 125 sec in specific impulse at sea level.

Introduction

Monopropellant propulsion systems have the advantages of liquid propellant propulsion and less complexity compared to bipropellant systems. Monopropellant systems are widely used for the Reaction Control System (RCS) of satellites or space launch vehicles, where the weight of the propulsion system is very important.

The first use of monopropellant for RCS was high-concentrated hydrogen peroxide in the SYNCOM satellite. Hydrogen peroxide was selected as a propellant for attitude control in projects Early Bird satellite, X-1 and X-15 experimental aircraft, and the Scout space launch vehicle [1, 2]. Hydrogen peroxide had been replaced by hydrazine because of a 20-30% lower specific impulse. Hydrazine thruster has become standard for RCS [3] in spite of it's high toxicity and potential carcinogenicity.

Interest in rocket-grade hydrogen peroxide was renewed in the mid 1990s as a nontoxic alternative to rocket propellants [1]. Recent studies have investigated rocket grade hydrogen peroxide as a monopropellant thruster [4-6], propulsion system for satellites [7-8], gas generator with dual catalyst bed [9], catalysts for decomposition of propellant [10-17], and to investigate long term storage characteristics [18].

A thruster consists of injector, reactor (including catalyst bed) and nozzle. The reactor is a key component, because the performance of the thruster mainly depends on the catalytic reaction at the reactor and the size of the catalyst bed. A scaled-down reactor of 1 cm of diameter and 4 cm of length was prepared and tested. The objective of a scaled-down reactor was to obtain the design data that is needed to determine the optimum diameter and length of the reactor for a 50 N thruster. A 50 N thruster was designed using a scale-up process and experimental data from the scaled-down reactor. The 50 N thruster was evaluated at both pulse and continuous mode operation.

The objective of this study was to develop a thruster using non-toxic propellant. Development of a monopropellant thruster using 90% H_2O_2 for application of RCS is described in this paper, including design and evaluation of a model reactor (scaled-down reactor) and a scaled-up 50 N level reactor.

Method and Preparation

1. Preparation of propellant

Hydrogen peroxide concentration diluted with water was determined by weight fraction between hydrogen peroxide and water. Decomposition of hydrogen peroxide (100 wt%) onto catalysts is described in Equation 1. An exothermic reaction occurs only if H_2O_2 concentration is more than 67 wt%, due to heat of vaporization of water product. The 90 wt% concentrated hydrogen peroxide as a monopropellant was prepared for thruster study. The quality of propellant was in accordance with the requirements of MIL-16005F, which defines the maximum allowable impurities for rocket grade hydrogen peroxide. The propellant density was 1392 kg/m^3 at 20 ^oC . Its adiabatic temperature and characteristic velocity were 750 ^oC and 936 m/s^2, respectively, from the CEA code [19].

$$H_2O_2(liquid) \rightarrow H_2O(gas) + \frac{1}{2}O_2(gas) + heat \qquad (1)$$

2. Catalyst preparation method

Platinum was selected as a catalyst for decomposition of hydrogen peroxide. The catalyst bed

was prepared from a γ-type bimodal alumina from Alfa Aesar, which displays 255 m^2/g of surface area, 1.14 cc/g of total pore volume, and 70 ㎛ and 5000 Å of median pore size. The preparation was performed with H_2PtCl_6 solution as a precursor, using the wetness impregnation method. Impregnation was followed by drying, calcination, and reduction. The catalyst coating process was performed two times. The final Pt/Al_2O_3 catalyst was prepared as 30% weight fraction based on alumina. Alumina support and prepared catalyst are shown in Fig. 1.

Fig. 1. Alumina support and prepared catalyst.

3. System setup and Data acquisition

Experimental setup was prepared prior to the thruster test. A schematic of the experimental thruster setup is shown in Fig. 2, which consists of pressurizer nitrogen gas tank, propellant tank, regulation systems, manual valves, solenoid valves, pneumatic actuator (Swagelok), mass flow meter (AW Company, ACM300, Coriolis type), force sensor (Kistler, 9217A), charge amplifier (Kistler, 5015A), sliding rail (LM guide), and valve control systems.

The SCXI modules (National Instrument, SCXI-1000, 1112, 1123) for data acquisition were introduced to measure temperature, pressure, thrust force, propellant mass flow, and valve on/off signals. A K-type thermocouple having an open junction was used for temperature measurement.

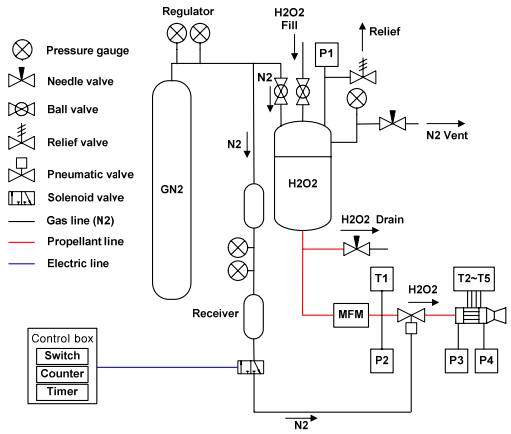

Fig. 2. Schematic of experimental setup

4. Evaluation methods of thrusters

Decomposition efficiency based on the temperature of product gases (η_T, Eq. 2) and efficiency of characteristic velocity (η_{C^*}, Eq. 3) were used to evaluate the reactor. Adiabatic temperature of propellant and theoretical characteristic velocity were calculated using the CEA code. Temperature of product gases, pressure at reaction chamber, and propellant mass flow were measured for calculation of two types of efficiency. Measurement of thrust force was also performed at the final thruster.

$$\eta_T = \frac{T_{product\ gases}}{T_{adiabatic}} \times 100 \tag{2}$$

$$\eta_{C^*} = \frac{C^*_{experiment}}{C^*_{theoretical}} \times 100 \ , \quad C^* = \frac{P_c A_t}{\dot{m}} \tag{3}$$

5. Design of a scaled down reactor

The scaled down reactor was designed (Fig. 3) and fabricated to evaluate the catalyst bed and to find the maximum propellant flow rate for this catalyst (Eq. 4). Main components were injector, catalyst bed and nozzle. A full cone type spray tip from Spraying System Co. was used as an injector to provide homogeneous distribution of propellant into the catalyst bed. Sauter Mean Diameter (SMD) of the injected water droplet was 135 ㎛ where pressure difference across the injector was 3 bar. The geometry for the reactor was 10 mm in diameter and 40 mm in length where the catalyst bed was filled in. Six ports were drilled to measure the temperature (T2-5, 1, 2, 3, 4 cm position at catalyst bed) and pressure (P3-4, before and after catalyst bed) in the reactor. The throat diameter was 1.5 mm.

$$\textit{Decomposition capacity of catalyst bed} = \frac{\textit{Propellant mass flow rate}}{\textit{Catalyst volume}} \tag{4}$$

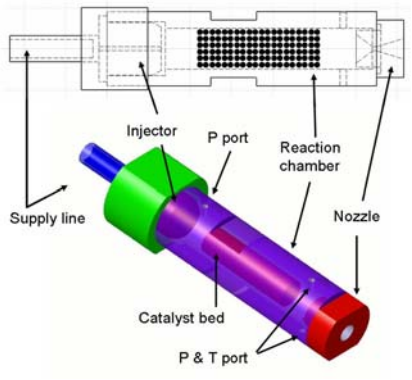

Fig. 3. Design of scaled down thruster

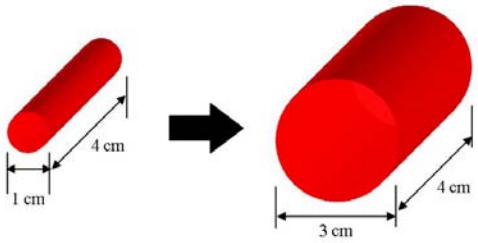

Fig. 4. Scale up of catalyst bed to the radial direction (left : catalyst for scaled down thruster, right : catalyst for scaled up thruster)

6. Design and evaluation of a 50 N thruster

The scaled down reactor was scaled up to a 50N reactor, which is able to fully decompose 33 gram/sec of 90 wt% hydrogen peroxide in a vacuum. The catalyst bed was 3 cm in diameter and 4 cm in length determined from experimental data of decomposition capacity of catalyst bed for the scaled down reactor. It was scaled up to the radial direction to decompose larger propellant flowrate than the scaled down reactor (Fig. 4). The 50N thruster was evaluated by decomposition efficiency based on temperature, η_T, efficiency of characteristic velocity, η_{C^*}, and measurement of thrust force.

Results

1. Scaled down thruster

A reaction test with scaled down thruster was performed to characterize the reactivity of Pt/Al_2O_3 catalyst by decomposition efficiency of propellant based on the temperature of product gases (Equation 2). Temperatures at 1, 2, 3, 4 cm from upstream of catalyst bed in the reactor were measured. Maximum temperature appeared in the catalyst bed, as a function of propellant mass flowrate (Fig. 5). The position of maximum temperature moved downstream in the reactor with increase of propellant mass flowrate. Two regions (A and B) were divided according to whether the fed propellant was fully decomposed or not (Fig. 5). Adiabatic temperature of 90 wt% hydrogen peroxide, 750 ^oC, was obtained at region A, where the propellant flowrate was lower than region B and fully decomposed. In region B, a maximum temperature was measured at the end of the catalyst bed and observed below adiabatic temperature at region B. Adiabatic temperature was not observed at any position on the catalyst bed in region B.

The efficiency of the characteristic velocity was calculated (Equation 3), which is a function of propellant mass flowrate (Fig. 6). The efficiency was over 90%, which was constant at an increased propellant mass flowrate below 4.0 g/s (region A). Afterwards, the efficiency sharply decreased with an increase of propellant mass flowrate over 4.0 g/s (region B). Maximum catalyst capacity, which was defined as allowable propellant mass flowrate/volume of catalyst bed, was observed at boundary of region A and B.

2. Scaled up thruster

A reaction test was performed with scaled up thruster, using test times of 20 seconds. The temperature profile at each position during the reaction is shown in Fig. 7. The test was done from a cold start (without heating of propellant and catalyst bed) at sea level. Propellant mass flowrate was 33 g/s, which is the required flowrate to produce 50 Newton thrust under vacuum conditions. Temperature sharply increased, reaching steady state value in several seconds after the main valve was opened. Adiabatic temperature was observed at the end of the catalyst bed. The decomposition efficiency, based on the temperature of product gases, was about 100%.

Pressure and thrust data are shown in Fig. 8. Propellant feeding pressure was 23 bar, and reaction chamber pressure was 16 bar. The thrust was 42 Newton and specific impulse was calculated as 125 sec at sea level test. The efficiency of the characteristic velocity as a function of the propellant mass flowrate is shown in Fig. 9. The efficiency was over 90% in the range of propellant flowrate below maximum capacity to the catalyst bed.

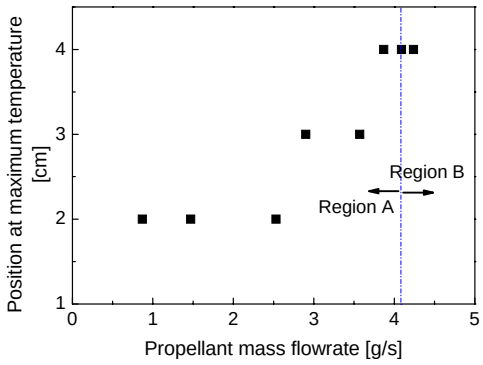

Fig. 5. Position at maximum temperature on the catalyst bed as a function of propellant mass flowrate (Region A: adiabatic temperature, Region B: below adiabatic temperature)

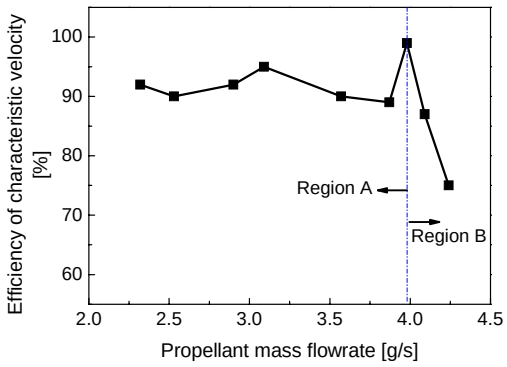

Fig. 6. Efficiency of characteristic velocity as a function of propellant mass flowrate

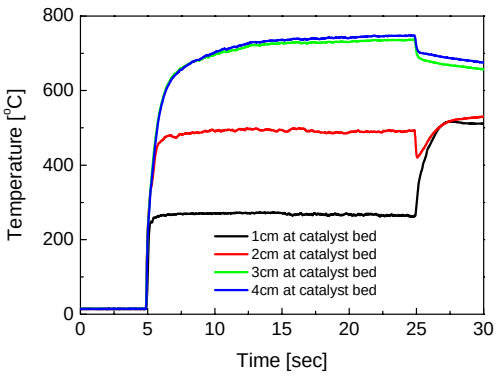

Fig. 7. Temperature measurement as a function of time at 50N thruster (mass flowrate: 33 g/s)

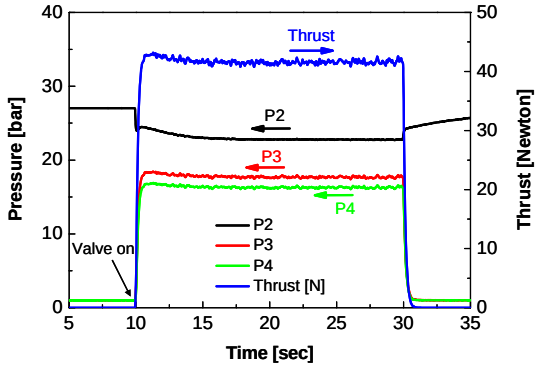

Fig. 8. Pressure and thrust measurement as a function of time at 50N thruster (mass flowrate: 34.8 g/s)

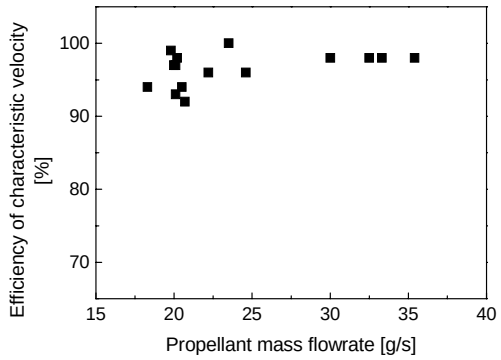

Fig. 9. Efficiency of characteristic velocity as a function of propellant mass flowrate at 50N thruster

Discussions

Silver and manganese have been widely used as decomposition catalysts for hydrogen peroxide. The melting point of silver is about 960 ^{o}C. Thus, a melting problem during thruster operating occurs using silver with highly concentrated hydrogen peroxide [20]. Manganese is a good candidate for decomposition of hydrogen peroxide, but manganese is difficult to hardly coat on support material [9]. Platinum was selected as a catalyst to avoid these problems. The melting point is much higher than adiabatic temperature of pure hydrogen peroxide, and its coating procedure has been well studied. In addition, platinum has been known as a promising candidate to have good reactivity with hydrogen peroxide [21].

The overall size of the thruster mainly depends on the size of the catalyst bed because all of the fed propellant needs to be decomposed onto catalyst [12]. The thruster is a compact size, if the decomposition rate of propellant on the catalyst bed is high, but bulky if the decomposition capacity of the catalyst bed (Eq. 4) is low because a larger catalyst bed is needed for full decomposition of the propellant flowrate. Thus, the decomposition capacity of the catalyst is a key parameter in designing a thruster for a 50 N thruster design. The mass flux, which is defined as propellant mass flowrate/frontal area of catalyst bed, usually indicates the decomposition capacity of the catalyst bed [13]. However, mass flux does not represent the total capacity of the catalyst because information about the length of catalyst bed is missing.

Equation 4 instead of mass flux is proposed to more accurately describe the capacity of the catalyst bed. The decomposition rate of the propellant was assumed to be proportional to volume of catalyst bed and inversely proportional to the propellant mass flowrate. Catalyst volume, which includes catalyst length, was used in place of frontal area of the catalyst bed in Equation 4. The smaller the size of thruster, the greater the capacity of the catalyst bed. Propellant mass flowrate was gradually increased to find the maximum decomposition capacity of the catalyst bed. The maximum decomposition flowrate of the propellant onto the catalyst bed was determined as a point where the decomposition efficiency is maximized and started to decrease with increase in the propellant flowrate. The objective of scaled down thruster was to obtain the decomposition capacity of the catalyst bed, which was developed at KAIST. The decomposition efficiency of temperature of product gas (Eq. 2) and efficiency of characteristic velocity (Eq. 3) were in agreement.

The 50 N thruster used the same catalyst as the scale downed thruster. The size of the catalyst bed was enlarged for full decomposition of designed flowrate, but having the same capacity value as the scaled down thruster. A catalyst bed, 3 cm in diameter and 4 cm in length, had full decomposition at 33 g/s (a flowrate for 50 Newton at vacuum).

A verification test of scaled up thruster was performed. Pressure in the reaction chamber (P4) was very stable and instability, like chugging instability, which frequently occurs in a small thruster chamber, was not observed. A stable reactivity was needed for the spray injector to guarantee an uniform injection of propellant into the frontal area of the catalyst bed. Almost all of the propellant was decomposed onto catalyst based on decomposition efficiency data. The measured specific impulse was 123 sec. The theoretical specific impulse at sea level is 128 sec. Thus, there was a 5 sec loss in specific impulse, which was from 15 degree of divergence angle of the nozzle. The thrust force to radial direction was due to the degree of divergence angle at the nozzle exit. It was concluded that the final thruster was properly designed with optimum size of the catalyst bed.

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