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Effect of dual-catalytic bed using two different catalyst sizes for hydrogen peroxide thruster

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ABSTRACT

For a catalytic bed in hydrogen peroxide based propulsion systems, a high pressure drop can cause significant problems. Hence, a dual-catalytic bed was suggested to reduce the pressure drop across the catalytic bed. Catalysts of two different sizes (1/8 inch, and 1.18–2.00 mm) were employed, which were fabricated using an impregnation method with MnO_2 and PbO as the active materials. The upstream and downstream sides of the dual-catalytic bed were loaded with the catalyst with dimensions of 1.18–2.00 mm and 1/8 inch, respectively. The effectiveness of the dual-catalytic bed was verified by conducting hot-fire tests with hydrogen peroxide monopropellant mode. The trends in the pressure drop across the catalytic bed and the characteristic velocity efficiency were investigated with respect to the mass flux and mass ratio of the loaded catalysts. As the mass ratio of the smaller catalyst was reduced to 18.3%, the pressure drop constantly decreased with an identical mass flux, though most of the fed hydrogen peroxide was still fully decomposed.

1. Introduction

Rocket-grade hydrogen peroxide has been widely used as a representative storable green propellant [1,2]. Moreover, it exhibits versatile characteristics as a storable propellant because it can be applied to various propulsion systems such as monopropellant thrusters [3–6], bipropellant thrusters [7–12], hybrid thrusters [13,14], gas generators [15], etc. When rocket-grade hydrogen peroxide is used as an oxidizer for bipropellant or hybrid thrusters, its auto-ignitability with a fuel owing to its high decomposition temperature (1022 K, 90 wt%) by the catalytic bed is a beneficial characteristic. This helps in simplifying the propulsion system and achieving high reliability. Propulsion systems using hydrogen peroxide have been developed with a wide range of thrust levels [3–14].

As the thrust level increases, the pressure drop across the catalytic bed becomes a significant design factor. This is because an increase in the pressure drop across the catalytic bed can adversely affect the thruster and the propulsion system. From the perspective of the propulsion system, the pressurization pressure increases with the increase in the pressure drop across the catalytic bed. This is related to the weight increment in the propulsion system and the higher requirements of the components. In addition, the excessive pressure drop across the catalytic bed causes several crucial issues with regard to the thrusters. The structural load deforms the distributor, which supports the loaded catalysts. The catalysts located at the downstream of the catalytic bed could mechanically rupture because of the pressure load, similar to that observed in the distributor, which can reduce the life of the thruster. For the monopropellant thruster, the pressure of the thruster is vulnerable to the chugging instability [3]. Thus, it is imperative to consider an appropriate pressure drop across the catalytic bed in the design of the catalytic bed. Several studies showed the relationship between the pressure drop across the catalytic bed and the mass flux [3,4,16]. The pressure drop across the catalytic bed could be controlled using this relationship. However, this design approach has a limitation in that the mass flux can be controlled only by modifying the cross-sectional area of the catalytic bed.

In the present study, a concept of the dual-catalytic bed using two difference catalyst granules was suggested to reduce the pressure drop within given dimensions of the catalytic bed. The effectiveness of the dual-catalytic bed was verified by conducting a hot-fire test with monopropellant mode. The trends in the pressure drop across the catalytic bed and the characteristic velocity efficiency were investigated with respect to the mass flux and mass ratio of the loaded catalysts. By applying the dual-catalytic bed, the pressure drop was remarkably reduced without reducing the reactivity of the catalytic bed.

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Nomenclature

c^*	Characteristic velocity ... m/s	ΔP_{dis}	Pressure drop across the distributor ... bar
G	Mass flux ... g/cm s^2	ΔP_{inj}	Pressure drop across the injector ... bar
P_c	Chamber pressure ... bar	η_{c*}	Characteristic velocity efficiency ... %
P_f	Propellant feeding pressure ... bar	λ	Mass ratio of loaded catalysts
ΔP_{cat}	Pressure drop across the catalytic bed ... bar		

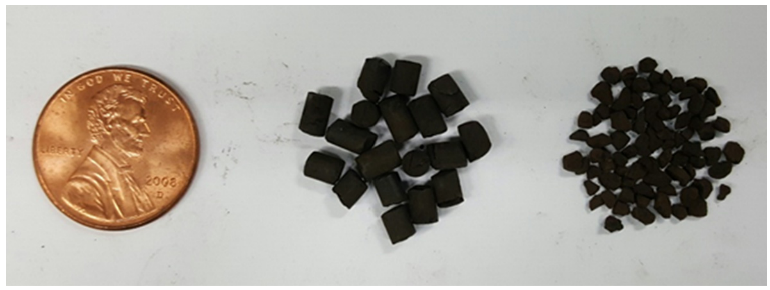

Fig. 1. Fabricated $MnO_2/PbO/Al_2O_3$ catalysts (center: 1/8 inch catalysts, right: 1.18–2.00 mm catalysts).

Table 1
Results of BET analysis.

	Al_2O_3	$MnO_2/PbO/Al_2O_3$	
		1/8 inch catalysts	1.18–2.00 mm catalysts
BET area, m^2/g	250.3	68.19	99.8
Pore volume, cm^3/g	0.8	0.24	0.34
Average pore size, mm	12.13	11.83	11.75

Table 2
Results of EDS analysis.

Element, wt%	Al_2O_3	$MnO_2/PbO/Al_2O_3$	
		1/8 inch catalysts	1.18–2.00 mm catalysts
O	40.64	33.5	32.8
Al	59.36	27.0	24.3
Mn	–	11.1	13.1
Pb	–	25.8	28.2
Na	–	2.5	1.6

2. Experimental apparatus

2.1. Preparation of the catalysts

MnO_2 and PbO were selected as the active materials. MnO_2 has been widely used as an active material for hydrogen peroxide. When MnO_2 is doped with PbO, the decomposition capacity is significantly improved [17]. A gamma phase alumina (Alfa Aesar) was used as a support. Two sizes of γ-alumina were utilized: 1/8 inch pellet and 1.18–2.00 mm (10–16 mesh size) granule. The 1.18–2.00 mm size support was produced from the 1/8 inch pellet by grinding. The catalysts were fabricated using an impregnation method. The fabrication process was identical to that given in another study [4]. Fig. 1 shows the fabricated catalysts. Energy dispersive spectroscopy (EDS) and Brunauer–Emmett–Teller (BET) analysis was conducted to analyze the coated material and porous characteristics of the catalysts. Tables 1 and 2 list the analysis results. Sodium is an impurity, the concentration of which was less than 3%.

2.2. Thruster

The experiments were conducted with a 90 wt% hydrogen peroxide/kerosene bipropellant thruster; however, it was operated in monopropellant mode without a kerosene injector for the study of the dual-catalyst bed. Hydrogen peroxide with a concentration of 90 wt% was used as the propellant, the density and adiabatic temperature of which are 1387 m^3/kg at 25 °C and 749 °C, respectively. The characteristic velocity is 940 m/s, which was calculated with the NASA Chemical Equilibrium and Application code [18]. A showerhead-type injector was designed with 110 orifices, each with a diameter of 0.4 mm. A 15° conical nozzle was designed with a nozzle throat diameter of 16.75 mm and a contraction ratio of 12.83. The catalytic bed diameter and length were 60 mm and 34.5 mm, respectively, with the aspect ratio of 0.583. The pressure was measured at the inlets of the propellant injector, catalytic bed, and combustion chamber. In the catalytic bed, three points were selected with the intervals of 17.5 mm, and 13.8 mm to acquire the pressure and temperature data. The pressure transduces (Sensys, Inc.) can be used to measure a maximum pressure of 70 bar with a pressure of ±0.15%. The K-type thermocouples were used to measure the temperatures. Fig. 2 shows the locations of the pressure transducers and thermocouples with the schematic of the thruster and the configuration of the catalysts. The specifications of the thruster were shown in Table 3.

2.3. Experimental apparatus

Fig. 3 shows the experimental apparatus. The 90 wt% hydrogen peroxide was supplied to the thruster from the pressurized tanks regulated with a nitrogen gas. The supply of hydrogen peroxide supply was controlled by the pneumatic and solenoid valves. The pressure data were acquired using a data acquisition card and a SCXI signal conditioning system with a 10-kHz low pass filter (National Instruments, Inc.). The sampling rate of the data acquisition card was 1000 samples/s. The mass flow rate of the hydrogen peroxide was measured and was controlled using a cavitating venturi valve. The accuracy of the mass flow rate was ±1.79%.

3. Result and discussion

The catalytic bed was loaded with two different sizes of catalysts. A mass ratio of loaded catalysts (λ) was defined as a ratio of the mass of the loaded 1.18–2.00 mm catalyst to the total mass of the loaded catalysts. To investigate the effect of the loaded proportion of each catalyst on pressure drop across the catalytic bed, and the decomposition performance of the catalytic bed, the mass ratio was controlled, as presented in Table 4. For