Comparison of Catalyst Support Between Monolith and Pellet in Hydrogen Peroxide Thrusters

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The effect of catalyst support on the performance of monopropellant thrusters was investigated. In the present study, two support materials (monolith honeycombs and alumina pellets) were tested and their relative performances were compared. A reference catalyst ($Na_{0.2}MnO_2$) was coated on both catalyst supports, and 90 wt% hydrogen peroxide was used as the monopropellant. Two test thrusters of different sizes were fabricated, and the performance of each thruster when using monolith honeycomb and alumina pellets as the catalyst bed was evaluated by measuring the product-gas temperature at the rear end of the catalyst bed and the pressure of the gas at the front and rear ends of the catalyst bed; during these measurements, the feed pressure of the propellant was fixed. Under the given test conditions, the performance of the thrusters was better when using alumina pellets as the catalyst support than when using monolith honeycomb. Since the monolith support was less reactive than the pellets, pressure buildup in the former case was relatively small; consequently, the chamber pressure and temperature were lower when using the monolith support than when using the pellet support. The pressure drop across the catalyst bed was moderate in both cases (0.02–0.1 bar in the case of a monolith and 0.3–0.7 bar in the case of a pellet catalyst).

Nomenclature

D = inner diameter of reactor, mm
d = diameter of pellet, mm
m = monolith
P = pressure, bar
p = pellet
R = reactor
T = thruster
TC = temperature inside the reactor
η_T = decomposition efficiency based on temperature, %

I. Introduction

ROCKET-GRADE hydrogen peroxide has been widely used as a monopropellant and oxidizer since the beginning of the space age. However, hydrogen peroxide is being gradually replaced with hydrazine, mainly because its specific impulse is 20% higher than that of the former. Further, dinitrogen tetroxide (N_2O_4), a storable liquid oxidizer, has replaced hydrogen peroxide in hypergolic bipropellant rockets [1]. Both hydrazine and nitrogen tetroxide are highly toxic; in particular, hydrazine is known to be a strong carcinogen with high toxicity. Because of the increasing concern regarding environmental safety, there has been a growing demand for nontoxic storable liquid propellants since the mid 1990s. Hydrogen peroxide is one of the most important nontoxic liquid propellants that can be used as a monopropellant thruster for upper-stage rockets and as an oxidizer for bipropellant engines in spacecrafts with rich space heritage. Hydrogen peroxide decomposes into steam and oxygen according to the catalytic reaction. The physical property of a catalyst support is an important factor that determines the rate of its decomposition.

A catalyst bed consists of an active material and its support. The active material catalyzes the decomposition of the monopropellant. However, the specific surface area of an active material itself is not sufficiently large; hence, the reaction rate observed when using such catalysts is low, as the reaction rate is proportional to the contact surface area of the catalyst. To increase the reaction rate, the catalyst is coated on a support material having a high specific surface area. The catalyst support plays an important role in determining the rate of the decomposition process, although it does not directly participate in the reaction. In general, an ideal support material should have high thermal/mechanical strength, physical/chemical stability, and a high specific surface area [2].

Various catalyst supports have been used for hydrogen peroxide decomposition. Lim et al. [3] used washcoated cordierite monolith as a support for a dual-catalyst bed in a gas generator, and Scharlemann et al. [4] used washcoated mullite monolith ($3Al_2O_3 \cdot 2SiO_2$). Barrio et al. [5] also used a monolith as a catalyst support. Lee et al. [6] employed Isolite®, a fire brick material, in a small monopropellant thruster that successfully propelled a toy rocket. Pellet-type supports have also been used by many research groups. An et al. [7,8] used cylindrical alumina pellets (γ-phase) in a 50-N class thruster. Pasini et al. [9] and Torre et al. [10] used spherical alumina grains. Xu et al. [11] used alumina grains with a mesh size of 12–40, and Tian et al. [12,13] produced Ir/Al_2O_3 and MnO-PbO/Al_2O_3 catalysts using alumina grains. Further, Sahara et al. [14] used metal foam as a catalyst support. Kuan et al. [15] used silver flakes as catalysts without any support material. Metallic silver screens were used by Blank et al. [16]. Literature survey revealed that monolith materials

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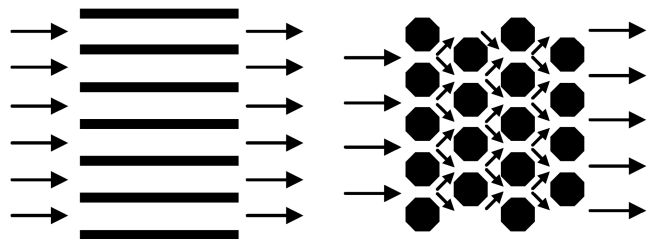
Fig. 1 Schematic of reactant flow at both monolithic and pellet catalyst beds.

Fig. 3 Mullite and Na$_{0.2}$MnO$_2$/washcoated mullite.

and pellets have been most frequently used as catalyst supports for hydrogen peroxide decomposition. Monolith supports, particularly those without a washcoat, has significantly less specific surface area (less than 1 m^2/g) than alumina pellets. Although the catalyst support plays a key role in enhancing the overall rate of decomposition of the monopropellant, very few comparative studies have been carried out on the efficiency of different catalyst supports. This is because most researchers in the past have carried out studies using the same support material and have not focused on the use of alternative support materials for a given reaction.

In this study, the relative performances of two representative catalyst supports (monoliths and alumina pellets) were evaluated. Figure 1 shows the reactant flow tendency at each support type. A straight channel flow was dominant at a monolith support, whereas a random flow occurred in the case of a pellet-type support. Na$_{0.2}$MnO$_2$ was used as the reference catalyst in both cases. Mullite honeycombs washcoated with alumina sol and γ-alumina pellets were prepared and used as supports before catalyst coating. The prepared catalyst supports were tested in identical thrusters using 90 wt% hydrogen peroxide as the monopropellant.

II. Catalyst Loading

A. Monolith Catalyst Bed

There are three types of monoliths that can be used as catalyst supports: cordierite (major content is silica), mullite (major content is alumina), and metal monoliths. All of these monolith supports have a low surface area; hence, they must be washcoated so as to increase their specific surface area and to enhance their adhesion with the catalyst. Consequently, a monolith that contains alumina as the major component is preferable, due to high adhesion between
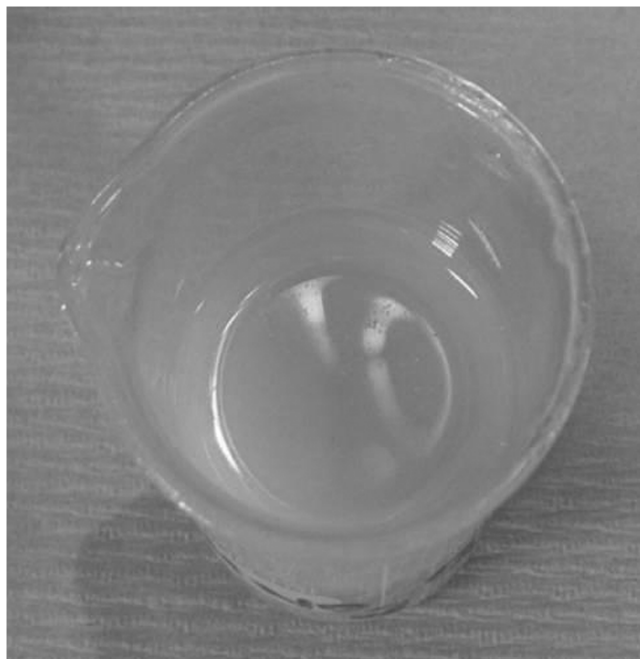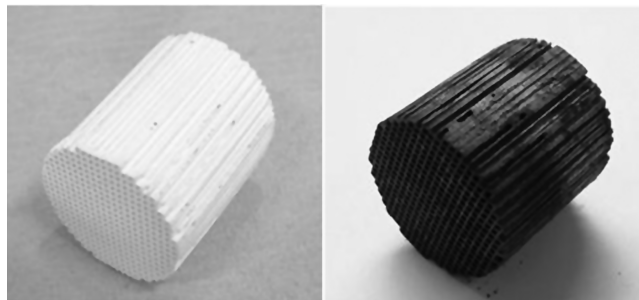

Fig. 2 Alumina sol solution.

monolith and washcoat layer (the main content of washcoat layer is alumina). The adhesion between washcoat layer and monolith is higher when the major ingredient of the monolith is the same element as in the washcoat layer (alumina). The main component in mullite is alumina, and that in cordierite is silica. Hence, mullite monolith (with 400 cells per square inch) was selected for the present study. Mullite was treated with a 65 wt% HNO$_3$ solution and calcined (300°C, 2 h) in order to remove the residual organic species. Alumina sol was prepared from commercial alumina (Disperal® P2 by Sasol Company). The washcoat layer was calcined (120°C, 1 h and 500°C, 2 h) after it was coated on the monolith support. The washcoat layer had 260 m^2/g of specific surface area, 0.47 cm^3/g of pore volume, and 6.9 nm of average pore size after calcination.

The washcoated monolith support was loaded with Na$_{0.2}$MnO$_2$ by wet impregnation using NaMnO$_4$ solution as the precursor. The support was then dried (50°C, 24 h) and calcined (500°C, 2 h). The sodium ions were washed out with water, and the catalyst-loaded monolith was finally calcined (750°C, 2 h), which was the adiabatic decomposition temperature of 90 wt% hydrogen peroxide. The physical properties of washcoat layer with active material was changed after final calcination. The layer with active material had 172 m^2/g of specific surface area, 0.35 cm^3/g of pore volume, and 8.1 nm of average pore size. The Brunauer–Emmet–Teller (BET) surface area and pore volume decreased and average pore size increased. Figures 2 and 3 show the alumina sol, mullite monolith, and the catalyst-loaded monolith.

B. Pellet Catalyst Bed

The procedure followed for coating the pellet catalyst bed was identical to that used for the monolith bed in all respects, except that it did not involve the washcoating step. Since the specific surface of the pellets was already high, no washcoat was required for the pellet catalyst bed. The pellets were made of γ-type alumina (255 m^2/g of specific surface area, 0.86 cm^3/g of pore volume, and 12.7 nm of average pore size), whose specific surface area was comparable with that of the washcoat layer (260 m^2/g). After final calcination, the catalyst bed had 162 m^2/g of specific surface area, 0.62 cm^3/g of pore volume, and 15.5 nm of average pore size. The BET surface area, pore volume, and average pore size (with ASAP 2420) before and after catalyst coating in both monolith and pellet supports are summarized in Table 1. The active material was found to be Na$_{0.2}$MnO$_2$ from the x-ray diffraction analysis. A little sodium ion remained, because it was not fully removed in the washing process.

If the diameter of the pellets is large, the propellant stream may flow through the gaps between the pellets. This phenomenon is

Table 1   Physical properties of alumina pellet and alumina washcoat layer

Contents	BET surface area	Pore volume	Average pore size
Washcoat layer (m1, m2)			
Before coating	260 m^2/g	0.47 m^3/g	6.9 nm
After coating	172 m^2/g	0.35 m^3/g	8.1 nm
Pellet or grain (p1, p2)			
Before coating	255 m^2/g	0.86 m^3/g	12.7 nm
After coating	160 m^2/g	0.62 m^3/g	15.5 nm

Table 2 Information on each catalyst sample

Catalyst (thruster)[a]	Weight, g				Weight percent	Size, mm
	Monolith	Al_2O_3	Active material	Total		
$m1$ ($T1$)	1.696	0.119	0.827	2.642	31.3	$10(d) \times 30(l)$
$m2$ ($T2$)	13.454	0.942	4.403	18.799	23.4	$30(d) \times 30(l)$
$p1$ ($T1$)	——	1.189	0.799	1.988	40.2	0.85–$1.13(d)$
$p2$ ($T2$)	——	8.640	1.522	10.162	15.0	$3.2(d)$

[a]Note that m denotes monolith, p denotes pellet, d denotes diameter, l denotes length, and 1 and 2 denote small and large thrusters, respectively.

known as channeling, because of which a uniform contact may not be formed between the propellant and the catalyst surface. In this study, the diameter of the pellets is set to approximately 10% of the inner diameter of the reaction chamber, as shown by the relation in Eq. (1), where d and D are the diameters of the pellet grains and the reaction chamber, respectively. The smallest diameter of commercially available pellets at $\frac{1}{8}$ in. was adequate in this criterion for the larger thruster tested in the present study. However, that size was too large to satisfy this criterion for the smaller thruster tested. For use in the small thruster, the pellets were crushed to 16–20 mesh (0.85–1.18 mm) so that the criterion in Eq. (1) was satisfied. Figure 4 shows the prepared $\frac{1}{8}$ in. and 16–20 mesh pellets coated with the catalyst:

$$\frac{d_{\text{pellet}}}{D_{\text{reaction chamber}}} \approx 0.1 \qquad (1)$$

The sizes of the catalyst beds and the weight fractions of the catalyst loaded on the bed are listed in Table 2; here, subscripts m and p pertain to the monolith and pellet supports, respectively. Subscripts 1 and 2 denote the smaller and large thrusters with inner diameters of
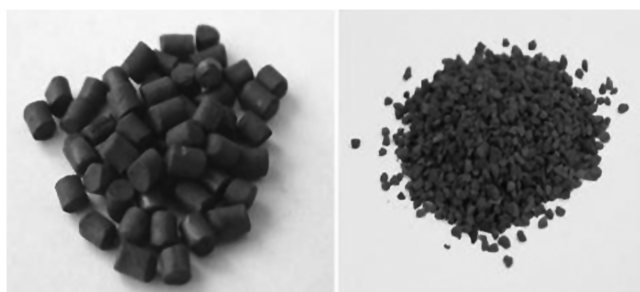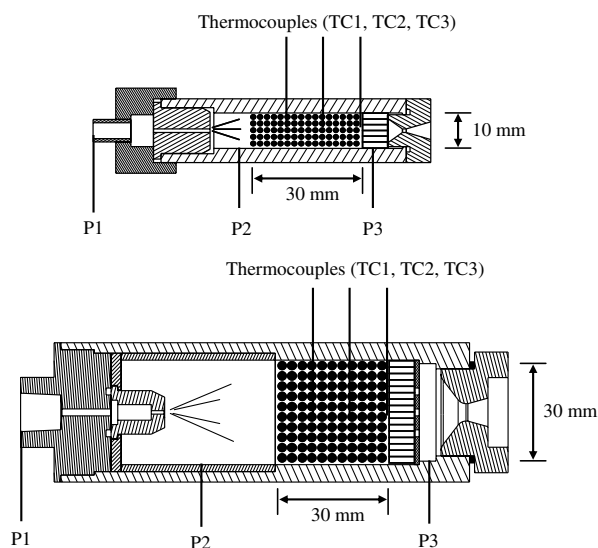
10 and 30 mm, respectively. In the coating process, a precursor solution was prepared with a low concentration and the coating of the active material was performed several times. For example, we coated the active material several times in the case of $p1$ to ensure that the manganese weight conditions between $m1$ and $p1$ were similar (0.827 g in $m1$ and 0.799 g in $p1$). Therefore, $p1$ and $p2$ had different values of weight percent.

III. Preparation for Test Reactions

Two thrusters of different sizes were used for evaluating the relative performance of the catalyst supports. The schematics of the thrusters are shown in Fig. 5. The inner diameters of the small and large thrusters were approximately 10 and 30 mm, respectively. The length of the catalyst bed was fixed at 30 mm for both thrusters. The volumes of the reaction chambers were 2.4 and 21.2 cm^3, respectively, in the case of the small and large thrusters. Throat diameters inside the nozzles were 1.0 and 5.0 mm at each thruster. Each thruster comprised a spray-type injector, catalyst bed, and a nozzle. Pressure probes were placed upstream ($P1$, feed pressure) and downstream ($P2$, pressure upstream of the catalyst bed) of the injector and at the rear end of the catalyst bed ($P3$, chamber pressure). Temperature probes were used to measure the temperature of the reactant at three different locations in the pellet catalyst bed: at distances of 10 mm ($TC1$) and 20 mm ($TC2$) along the axis of the thruster and at the rear end of the thruster ($TC3$). However, only the temperature ($TC3$) at the rear end of the catalyst bed was measured in the case of the monolith catalyst bed so as to avoid drilling holes on monolith structure for insertion of the temperature probes.

The propellant pressurized by high-pressure nitrogen was supplied to the thruster through a Coriolis-force-type mass flow meter that measured the flow rate of hydrogen peroxide. The propellant flow rate was determined from feed pressure $P1$ and measured by the mass flow meter. The operation of each thruster lasted for 10 s, over which pressures and temperatures at various locations in the thruster were recorded. The sampling rate of data acquisition was 100 Hz with a 10 kHz filter. All of the experiments were carried out using 90 wt% hydrogen peroxide as the propellant.

IV. Results and Discussions

A. Results Obtained with the Small Test Thruster ($T1$)

Table 3 shows a comparison of the pressures and temperatures recorded during each test carried out using the pellet and monolith

Fig. 4 $Na_{0.2}MnO_2/Al_2O_3$ catalyst; $\frac{1}{8}$ in. pellets (left) and granules with a mesh size of 16–20 (right).

Fig. 5 Test thrusters $T1$ and $T2$.

Table 3 Temperatures and pressures observed when using $T1$

$P1$, bar	$P2$, bar	$P3$, bar	H_2O_2 flow rate, g/s	TC_c, °C	η_T, %
		Monolith catalyst bed			
8.6	4.9	4.9	3.26	176	21
13.1	7.5	7.5	3.63	198	24
19.1	9.4	9.4	3.82	209	25
24.0	10.2	10.2	3.88	211	26
		Pellet catalyst bed			
8.3	8.1	7.8	1.82	643	85
13.1	12.1	11.6	2.36	688	92
18.8	16.2	15.6	2.72	716	95
24.4	20.1	19.4	2.95	736	98

catalyst beds. TC_c denotes the $TC3$ value observed for the monolithic catalyst and the highest thruster temperature recorded for the pellet catalyst. Table 3 also shows the feed-pressure conditions. The propellant was fed into the reaction chamber at feed pressures ranging from 8 bar to 25 bar. The propellant flow rate was high at high feed pressures. The pressure drop across the catalyst bed ($P2$-$P3$) at each type was negligible (-0.02–0.1 bar) for the monolith type and 0.3–0.7 bar for the pellet type. The results showed that the temperature $TC3$ and chamber pressure $P3$ of the product gas were different in the pellet and monolith catalyst beds, although the tests were performed under similar feed-pressure conditions. Generally, in the monolith catalyst bed, $P3$ was low, although the propellant flow rate was high. At the rear end of the monolith catalyst bed, $TC3$ was approximately 200°C; this temperature was barely above the boiling point of hydrogen peroxide. However, $TC3$ was between 643 and 736°C in the pellet catalyst bed. The decomposition efficiency based on the product-gas temperature [Eq. (2) is also shown in Table 3]:

$$\eta_T = \frac{T_{\text{product gas}} - 298}{T_{\text{adiabatic}} - 298} \times 100 \qquad (2)$$

Figure 6 shows the pressures and temperatures measured for the monolith catalyst bed. The built-up chamber pressure and temperature were 7.5 bar and 198°C, respectively. The propellant flow rate was 3.63 g/s at a feed pressure of 13.1 bar. Figure 7 shows the pressure– and temperature–time histories for the pellet catalyst bed when the propellant flow rate was 2.72 g/s. The built chamber pressure and temperature of the reaction chamber in the case of the pellet catalyst bed were 15.6 bar and 716°C, respectively, which were significantly higher than those obtained in the case of the monolith catalyst bed. It is noteworthy that the chamber pressure in the pellet catalyst bed was higher than that observed in the mullite monolith bed, although the mass flow rate of the propellant in the case of the former (2.72 g/s) was lower than that in the case of the latter (3.63 g/s). This meant that the activity of the pellet catalyst bed was higher than that of the monolith catalyst bed. The monolith
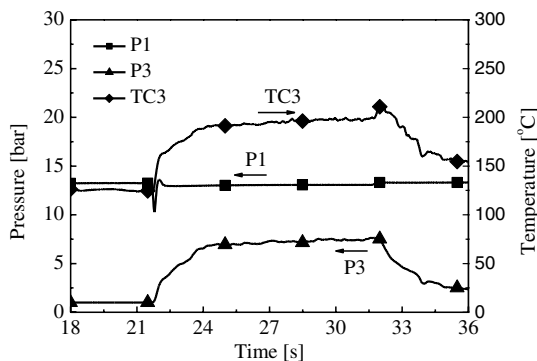

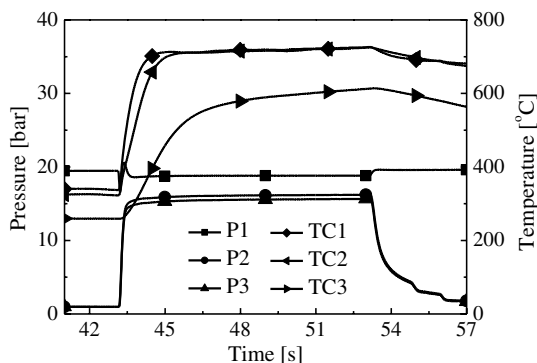**Fig. 6 Temperature– and pressure–time histories for $T1$ with $m1$ catalyst (3.63 g/s).**

Fig. 7 Temperature– and pressure–time histories for $T1$ with $p1$ (2.72 g/s).

catalyst bed showed lower chamber pressure because of the lower decomposition efficiency from the lowly built decomposition temperature.

The pressure–time history in the reaction chamber could be explained as follows: The propellant valve was opened when the propellant was injected into front end of the catalyst bed. The reaction chamber was maintained at atmospheric pressure before the valve was opened, and the pressure difference across the injector during the initial stages of the reaction was higher than that under steady-state operation conditions; because of this, the mass flow of propellant into the chamber was greater than that desired. A greater amount of the propellant was injected into the chamber during this transient (unsteady) region at earlier stage of reaction than in the steady state. In an ideal case, the injected propellant completely decomposes into steam and oxygen, and $P3$ increases gradually. With an increase in $P3$, the pressure drop across the injector ($P1$-$P2$) as well as the propellant flow rate decrease. Finally, $P3$ reaches the desired value at which the propellant flow rate is adequate to maintain the chamber pressure at the desired level. If the catalyst bed cannot drive the decomposition of the propellant to completion, $P3$ remains less than the theoretical pressure; this results in an increase in the pressure drop across the injector and hence an increase in the amount of propellant fed into the chamber. Ultimately, the chamber pressure reaches a steady value at which it balances the propellant flow rate. In our study, the observed chamber pressure $P3$ and the reactant temperature in the case of the monolith catalyst beds were significantly lower than those expected under ideal operation conditions, because the catalyst bed could not drive the decomposition reaction to completion.

B. Results Obtained with the Large Test Thruster ($T2$)

To investigate the performance of the catalyst support in reaction chambers of different sizes, hydrogen peroxide decomposition was carried out in a large thruster ($T2$) with a reaction volume of 21.2 cm^3 using a monolith catalyst bed ($m2$) and a pellet catalyst bed ($p2$). Each experiment lasted for 10 s at various feed pressures. The temperature of the product gas at the rear end of the catalyst bed was measured at different pressures for both of these catalyst beds; the obtained results are presented in Table 4.

Figure 8 shows the temperatures measured for the two catalyst beds under similar conditions of propellant flow. In these tests, the feed pressure was not the same because the reactivities of the two catalyst beds were different. The feed pressures were 9.0 bar in the case of the monolith catalyst bed ($m2$) and 15.5 bar in the case of the pellet catalyst bed ($p2$), and the propellant flow rates were matched at these pressures. As observed in the tests performed with $T1$, the reactivity of the monolith catalyst bed was considerably lower than that of the pellet catalyst bed. The product-gas temperature in the case of the monolith catalyst bed ($TC3$) was 173°C, which was slightly greater than the boiling point of hydrogen peroxide. In the monolith catalyst bed, the injected propellant could be vaporized only for a certain reaction chamber size. On the other hand, in the case of the pellet catalyst bed, the chamber temperature in $TC1$ was approximately 200°C and that in $TC2$ was between 300 and 400°C. Further, $TC3$ was 706°C, which was slightly lower than the adiabatic decomposition temperature of 90 wt% hydrogen peroxide.

Table 4   Temperatures and pressures observed when using $T2$

$P1$, bar	$P2$, bar	$P3$, bar	H_2O_2 flow rate, g/s	TC_c, °C	η_T, %
Monolith catalyst bed					
9.0	5.4	5.3	30.8	173	20
13.5	4.9	4.8	49.0	685 [a]	91 [a]
17.8	2.7	2.6	59.0	55 [b]	4 [b]
Pellet catalyst bed					
15.5	8.6	8.3	30.9	706	94
20.6	15.3	15.0	37.9	675	90
25.2	17.7	17.4	45.9	227	28

[a]Preheated, just peak value, and still decreased.
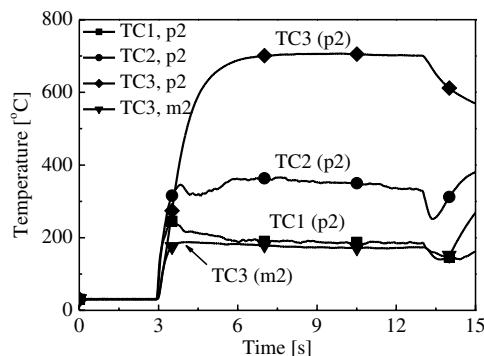[b]Flushing out of hydrogen peroxide.

Fig. 8   Temperature–time history for $T2$ with $m2$ and $p2$ catalysts (30.8 g/s for the monolith catalyst bed, 30.9 g/s for the pellet catalyst bed).
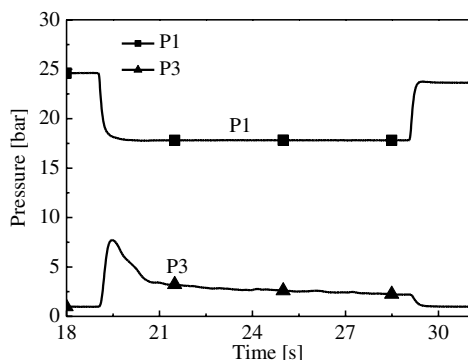

Fig. 9   Pressure–time history for $T2$ with $m2$ catalyst (59.0 g/s).
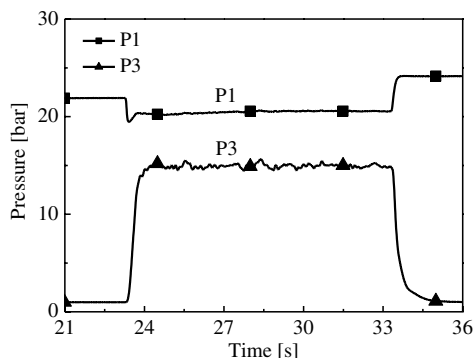

Fig. 10   Pressure–time history for $T2$ with $p2$ catalyst (37.9 g/s).

Figures 9 and 10 show the difference in the time histories of $P3$ observed for the monolith and pellet catalyst beds. Each test reaction with these catalyst beds was performed at similar feed pressures of 17.8 bar ($m2$) and 20.6 bar ($p2$). Therefore, the built chamber pressures in these two cases were different, due to the difference in the reactivities of these catalysts; hence, the flow rates of the propellant in these two cases were also different. As is evident from Fig. 9, with the monolith catalyst bed, the built chamber pressure was very low at the transient region of early stage of reaction because of the low decomposition efficiency; hence, the amount of propellant supplied to the reaction chamber was markedly greater than that in the case of the pellet catalyst bed. Finally, the reaction chamber was completely filled with hydrogen peroxide, which was then flushed out of the chamber. On the other hand, in the pellet catalyst bed, whose reactivity was better than that of the monolith catalyst bed, complete decomposition of the propellant occurred in the transient region, and the built chamber pressure was stable.

In all of the tests, a greater amount of the propellant was supplied into the reaction chamber when using the monolith catalyst bed than when using the pellet bed. Despite this increase in the amount of the propellant fed to the reaction chamber, the built-up chamber pressure was low in the case of the monolith bed because of low decomposition temperature. This indicated the relatively low reactivity of the monolithic catalyst bed as compared with that of the pellet catalyst bed.

The amount of the deposited catalyst ($Na_{0.2}MnO_2$) was also thought to have a significant effect on hydrogen peroxide decomposition. The amounts of $Na_{0.2}MnO_2$ loaded on $m1$ and $p1$ catalyst beds were similar (0.827 g and 0.799 g, respectively) in the tests carried out in $T1$. On the other hand, during the tests performed in $T2$, the amount of $Na_{0.2}MnO_2$ loaded on the monolith catalyst bed (4.403 g) was almost three times that of $Na_{0.2}MnO_2$ loaded on the pellet catalyst bed. However, the reactivities of the $m1$ and $m2$ were found to be significantly lower than those of $p1$ and $p2$ in the tests carried out using the two of thrusters, although the amount of $Na_{0.2}MnO_2$ loaded on $m1$ and $m2$ was greater. The low reactivity of the monolith catalysts could be due to the following reasons. For a given reaction volume, the total surface area of the washcoated monolith bed was low, because of the presence of a large number of vacant channels; on the other hand, the surface area per unit reaction volume of the pellet catalyst bed was significantly high, because of the porous nature of the pellets. This indicated that the pellet support had a significantly lower dead volume than the monolith support when it was filled in the reaction chamber. Further, the mixing efficiency of the reactant and the product during the decomposition process was better when using the pellet catalyst than when using the monolith catalyst, because of the aforementioned structural difference. Additionally, heat and mass transfer were not very efficient in the monolith catalyst bed, because of the presence of channels in its structure; however, efficient heat and mass transfer was observed in the pellet catalyst bed, because the pellets provided complex flowpaths for mixing. Therefore, for the same reaction volume, the reactivity of the monolithic catalyst could not be brought to the level of that of the pellet catalyst.

In this paper, the performance of the monolith catalyst bed was much worse than that of the pellet (or grain) catalyst bed, because of mixing effect. There was another possibility that the coating method of the monolith was not optimized. The performance of the monolith catalysts can be better or worse, depending on the coating method. The catalyst activity varies with many parameters: active material, precursor selection, weight percent of active material, physical properties of support (washcoat), washcoat weight percent, adhesion between active material and support, crystal size of active material, and so on. Additionally, if the coating process is different, the activity will be different, although we use the same active material, washcoat, and monolith. Because of this possibility, reactivities of the monolith-based catalyst from extensive literatures were compared. If the performance of the monolith in this test is similar to that from previous literature, it can be thought that the coating of active material on the monolith catalyst is reasonable. Several results related to the monolith catalyst are summarized in Table 5. In this comparison, the flow rate A, catalyst reactor volume (catalyst volume) B, decomposition efficiency (C^*, C), and its activity (catalyst capacity) were indicated. The activity was simply compared as the value of $A/B \times C$. In this calculation, the value for the monolith type was similar and it ranged from 0.09 to 0.31. A value of 0.36 was calculated in this paper and was reasonable as compared with those of other monolith catalyst beds in H_2O_2 decomposition. It represented that the low reactivity in a monolith-based catalyst was not from the optimization problem in the catalyst coating process, but from originally structured channels of the monolith support.

In this test, the BET surface area between two supports (washcoat layer and alumina pellet) was similar, but pore volume and average pore size were different. The differences could arise in the catalytic reactivity because of this problem (different pore size and volume); however, in the present study, propellant flow tendency according to support types was assumed as the primary effect to decomposition efficiency, and the effect of the pore volume and size on the thruster performance was assumed as the secondary effect. Therefore, specific research will be valuable to separate these two effect (support types and physical properties of supports).

Table 5 Decomposition capacity of the monolith-based catalyst from previous literature[a]

Researcher	Catalyst/monolith type	Cell density	Flow rate A	Reactor volume B	C-star efficiency C	Monolith catalyst capacity ($A/B \times C$)
Rang et al. [17]	MnO_2 + LSC/cordierite	300 cpi	5.7 g/s	58.9 cm^3	over 90%	0.09
Scharlemann et al. [4]	MnO_2/mullite	400 cpi	0.36 g/s	1.5 cm^3	99%	0.24
An and Kwon [18]	Pt/cordierite	900 cpi	0.8 g/s	3.14 cm^3	96%	0.24
Lim et al. [3]	Pt/cordierite	300 cpi	10 g/s	24.5 cm^3	75%	0.31
This paper	$Na_{0.2}MnO_2$/Mullite	400 cpi	3.88 g/s	2.4 cm^3	22%	0.36

[a]All monolith supports were washcoated with alumina; LSC means La0.8Sr0.2CoO3, Pt means platinum, and cpi means cells per square inch.

In comparison tests of two catalyst beds, the same feed-pressure condition was used instead of the identical mass-flow-rate conditions. First, an identical mass flow condition was intended for reaction tests, which provides a reasonable comparison. However, the difference between the catalyst activities of the two types appeared to be quite high and, therefore, ensuring identical mass flow conditions was impossible. The mass flow was determined by the pressure drop across the injector ($P1$-$P2$). $P2$-$P3$ represented the pressure drop across the catalyst bed, which was negligible (below 1 bar). Therefore, $P2$ was determined by $P3$, which was determined by the decomposition efficiency of the injected propellant (reactivity of catalyst). If $P1$ was freely set using a regulator, $P3$ (chamber pressure) could not be regulated, because it was determined by the reactivity. Therefore, ensuring the same mass-flow-rate condition was impossible when the difference between the catalyst activities was high, although the propellant mass flow rate was increased or decreased to some extent by increasing or decreasing the feed pressure $P1$. Therefore, the identical (or similar) mass-flow-rate condition occurred once in the $T2$ test (Table 4): 30.8 g/s (monolith) and 30.9 g/s (pellet).

On the other hand, one problem occurred when feed pressure was regulated to satisfy the mass flow rate at two test conditions. If the activity of the catalyst bed was high, the mass flow rate was relatively small, because of the high chamber pressure ($P3$). To increase the mass flow rate, the feed pressure $P1$ should be increased, which induced a higher chamber pressure ($P3$). Generally, the catalyst reactivity varied (generally increased) when the chamber pressure increased. This was because increasing the density of the vapor phase led to an increase in the residence time, which enhanced the decomposition process [7]. Therefore, the decomposition efficiency could not be compared fairly when the condition of the same mass flow rate but different chamber pressure was applied at a given thruster setting. A large difference appeared in the decomposition efficiency, due to pressure effect. For this reason (pressure effect), each catalyst was evaluated under similar feed-pressure conditions instead of similar mass-flow-rate conditions.

V. Conclusions

The reactivities of two catalyst beds with different supports (monolith and pellets) were investigated for the decomposition of hydrogen peroxide. A reference catalyst, $Na_{0.2}MnO_2$, was used to identify the effects of the catalyst support characteristics. Different catalysts were filled into model thrusters and tested for their ability to catalyze the decomposition of hydrogen peroxide.

Under similar feed-pressure and propellant flow conditions, the temperature and chamber pressure in the tests performed with the pellet catalyst were high, although the propellant flow rate was low, because of differently built decomposition temperature from the difference in reactivity between the two catalyst beds. Additionally, the reactivity of the pellet catalyst was better than that of the monolithic catalyst, although the amount of $Na_{0.2}MnO_2$ deposited on the pellets (0.799 and 1.522 g for $p1$ and $p2$, respectively) was less than that deposited on the monolith catalyst (0.827 and 4.403 g for $m1$ and $m2$, respectively), due to the following two reasons. First, the thickness of the washcoat layer on the monolith support could not be increased beyond a limit; hence, it was difficult to increase the total surface areas of the washcoated monolith to match those of the alumina pellets. Second, heat and mass transfer were ineffective in

the case of the monolith, due to the large number of channels present in its structure. Hence, its efficiency for hydrogen peroxide decomposition remained lower than that of the pellet catalyst even when the feed pressure, propellant flow rate, and reaction volume were identical in both cases. Further, the mixing capability of the reactant and the product was poor in the case of the monolith bed.

The reactivity of the monolithic catalyst can be enhanced if the cell density of the catalyst and/or the thickness of the washcoat layer are increased. The results of this study show that reactivity of pellet catalysts is generally better than that of monolith catalysts.

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