

Technical Notes

Transient Behavior of H_2O_2 Thruster: Effect of Injector Type and Ullage Volume

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Nomenclature

A = cross-sectional area, mm^2
 C_d = discharge coefficient
 ΔP = pressure differences, bar

Introduction

ROCKET-GRADE hydrogen peroxide has been used as a monopropellant and a storable oxidizer. However, because of the demand for a higher specific impulse, hydrazine and N_2O_4 are being used as the monopropellant and storable oxidizer, respectively. Recently, due to concerns regarding propellant toxicity, there has been a renewed interest [1] in the use of H_2O_2 in propulsion systems [2–10].

A monopropellant thruster is operated in either the continuous or pulse mode. The thrust force and pressure instability are important issues in the continuous mode. For generating the desired thrust, the catalytic reactor size required for completely decomposing the propellant must be determined [8]. However, in the pulse mode (the main operation mode for attitude control systems), the response characteristics of the thruster are important. The catalyst activity, thruster component design (including the injector design), manifold volume, ullage volume in the reactor, and operating pressure influence the thruster response time. Tian et al. investigated the response time when using a combination of PbO and MnO_2 catalysts [11]; they found that $\text{Ir}/\text{Al}_2\text{O}_3$ is unsuitable for use as a catalyst in a H_2O_2

monopropellant thruster [12]. Xu et al. studied the activities of various catalysts during H_2O_2 decomposition [13]. El-Aiashy et al. reported that the catalyst activity of MnO_2 increased when ZnO was added [14]. Hasan et al. reported that the activity of MnO_2 increased when promoters such as Ni, Cu, Bi, and Ce were added [15].

None of the aforementioned studies have addressed the effect of thruster design parameters on response times, although a few researchers have measured the thruster response time. Optimization of the thruster design (determination of the appropriate injector and ullage volume in the reaction chamber) can also influence the response characteristics. Therefore, we investigate the response characteristics of H_2O_2 monopropellant thrusters for three different thruster designs and measure the response times by varying the injector type, reactor volume, and catalyst grain size. A $\text{MnO}_2/\text{Al}_2\text{O}_3$ catalyst is used for the decomposition of concentrated H_2O_2 (90 wt%).

Catalyst and Thruster Design

Catalyst

MnO_2 was used as the active material for the decomposition of H_2O_2 because of its superior activity [16]. MnO_2 from a NaMnO_4 solution as a precursor (Aldrich) was deposited on alumina pellets (Alfa Aesar) by an impregnation method. $\text{MnO}_2/\text{Al}_2\text{O}_3$ (30 wt%) of two different sizes were prepared (Fig. 1): 1/8 in. pellets, and granules with a mesh size of 16–20 (0.85–1.18 mm).

Thruster Design

Three thruster models were developed for measuring the response time. Cross-sectional views of each thruster are presented in Fig. 2 (cases 1, 2-1, and 2-2). The main components of each thruster were an injector, a catalytic reactor (including a catalyst bed), a distributor, and a nozzle. The injector type and reactor size for each model thruster are listed in Table 1. The reactors in cases 1 and 2-1 were 30 mm in diameter and 40 mm in length and were filled with the catalyst. The volume of the case 2-2 reactor was one-half that of the case 1 and 2-1 reactors. The thrusters were classified into case 1 or 2-1 (or 2-2), depending on the injector type. In case 1, the spray injection method was used for obtaining a uniform droplet distribution. Here, for uniformly spraying H_2O_2 on the frontal surface of the catalyst bed, it was necessary to maintain a considerable distance between the injector and the catalyst bed, as the droplets emerging from the spray tip were not directed horizontally, but at an angle to the horizontal. However, in case 2, a showerhead injector with 19 orifices (diameter: 300 μm) was used. With the showerhead injector, it was difficult to obtain a uniform distribution of droplets as obtained in spray injection. However, the distance between the injector and catalyst bed when using the spray injection method was minimized; this minimized the ullage volume in the thruster. Therefore, the thruster in case 2-1 was shorter than that in case 1, although both had identical catalytic reactors. The discharge coefficient (C_d) and cross-sectional areas (A) of the orifices primarily determine the propellant flow rate at a given pressure difference (ΔP) across the injector. Two injectors are designed with identical $C_d \cdot A$ values so that the corresponding propellants have equal flow rates at a given ΔP . Figure 3 shows photographs of the two injectors.

All thrusters had pressure ports upstream/downstream of the injector (P1, P2) and a reaction chamber downstream of the catalytic reactor (P3). The volume of the reaction chamber downstream of the catalyst bed and the nozzle geometry were identical in all thrusters.

Experimental Setup and Test Method

The propellant was pressurized by pressure-regulated N_2 and supplied to a thruster. A pneumatic actuator (Swagelok) operated

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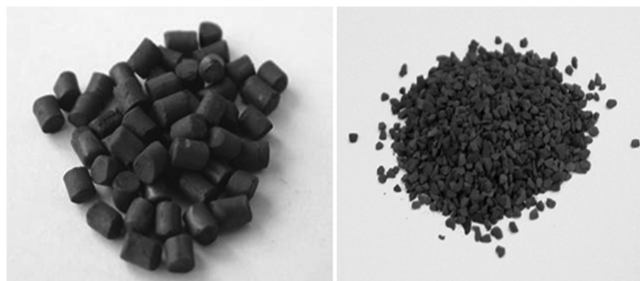


Fig. 1 $\text{MnO}_2/\text{Al}_2\text{O}_3$ catalyst: a) 1/8 in. pellets, and b) granules with a mesh size of 16–20.

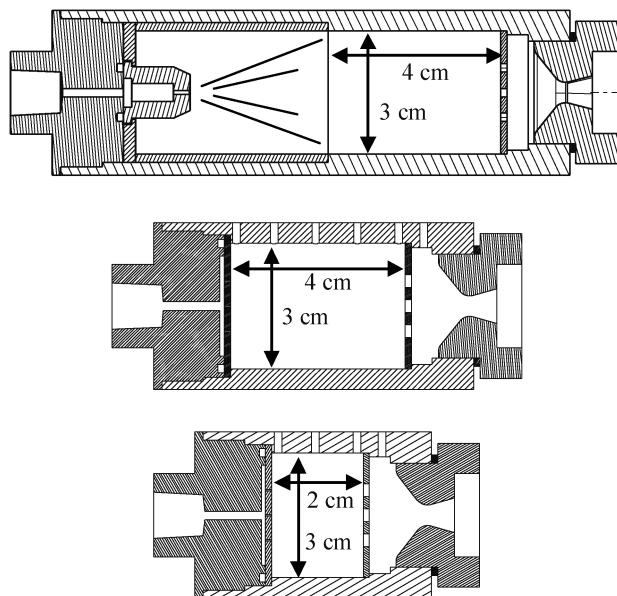


Fig. 2 Model thruster cases: a) 1, b) 2-1, and c) 2-2.

using a solenoid valve was used as the propellant valve. A data acquisition card and SCXI modules (10 kHz filters; National Instruments) were used to measure the temperature and pressures. The sampling rate during data acquisition in the reaction tests was 1000 samples/s. A K-type thermocouple with an open junction was used for fast response during temperature changes.

A pulse was divided into several sections, and the response time of a thruster was accordingly separated into decomposition delay (ignition delay), pressure rise time, and pressure decay time [17]. Decomposition delay occurs when a monopropellant thruster is used and is defined as the time elapsed between the generation of the valve-open signal and the time the chamber pressure (P_3) reaches 1% of its steady-state value. The pressure rise time is the time taken for P_3 to increase from 1 to 90% of its steady-state value; the pressure decay time is the time elapsed between the generation of the valve-off signal to the time P_3 reaches 10% of its steady-state value.

For measuring the response time, an indirect method was used to identify the voltage signals indicating the opening and closing of the valve. The pressure (P_1) upstream of the propellant valve decreased slightly when the propellant valve was opened, and the propellant flowed into the propellant tube. P_1 increased when the valve was being closed. The initial decrease and increase in P_1 and P_2 were

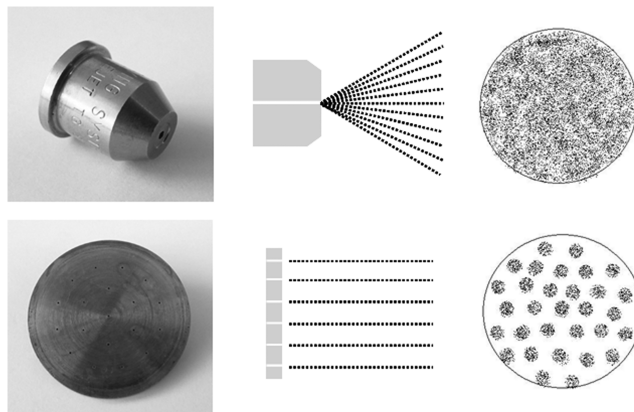


Fig. 3 Different types of injectors and droplet patterns: a) spray injector, and b) showerhead injector.

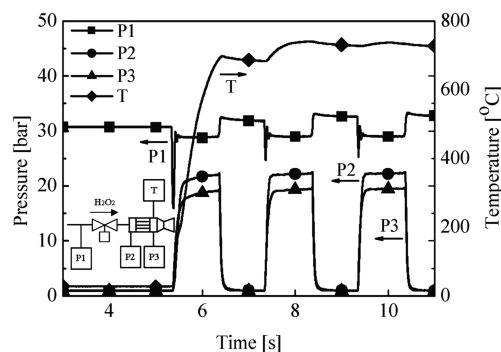


Fig. 4 Transient region (case 2-2, granules with a mesh size of 16–20).

assumed to correspond to the generation of the valve-opening and valve-closing signals, respectively.

Each thruster was filled with the prepared catalysts. The propellant was subjected to a pressure of 30 bar and the flow rate was ~ 45 g/s. Pulse tests were performed, and the time taken for opening and closing the propellant valve was 1.0 s (duty cycle: 100%). Response times were measured and averaged for three continuous pulses.

Results and Discussions

Effect of Injector Type and Ullage Volume

Table 1 lists the test cases. First, reaction tests were performed with the case 1 and 2-1 thrusters. The pellet catalyst was used, and the response times were compared. The decomposition delay, pressure rise time, and pressure decay time were 32, 192, and 325 ms for the case 1 thruster and 26, 119, and 216 ms for the case 2-1 thruster, respectively. The main difference between these two thrusters was the injector type. The long decomposition delay in case 1 was caused by the long distance traveled by the droplets from the injector to the catalyst bed. In the case 2-1 thruster, the rise time was fairly fast and was related to the ullage volume in the reactor. The pressure rise time and pressure decay time increased with the ullage volume.

Effect of Catalyst Grain Size

Pellet (1/8 in.) and granular catalysts (16–20 mesh) were used separately in tests involving the case 2-1 thruster. The response times in the former case were considerably shorter than those in the latter

Table 1 Model thrusters and test cases

Thruster	Case 1	Case 2-1	Case 2-2
Injector type (orifice no.)	Spray (1)	Showerhead (19)	Showerhead (19)
Reactor size, cm	3(d) \times 4(l)	3(d) \times 4(l)	3(d) \times 2(l)
Catalyst size	1/8 in.	1/8 in. and 16–20 mesh	16–20 mesh

Table 2 Response times (in milliseconds) for each test, where parenthesis indicate standard deviation

Thruster	Catalyst size	Decomposition delay	Pressure rise time	Pressure decay time
Case 1	1/8 in.	32 (4)	192 (44)	325 (23)
Case 2-1	1/8 in.	26 (1)	119 (13)	216 (2)
Case 2-1	16–20 mesh	12 (2)	114 (1)	106 (2)
Case 2-2	16–20 mesh	14 (2)	108 (5)	94 (5)

case. The decomposition delay, pressure rise time, and decay time were 12, 114, and 106 ms, respectively.

A decrease in the grain size of the granular catalyst affected the catalytic activity and ullage volume positively. Catalyst grains with large diameters resulted in large diffusion resistances; this prevents H_2O_2 from reacting with the inner pellet catalyst, and the diffusion controlled the total reaction rate at elevated temperatures [18]. The catalytic activity possibly increased as the catalyst grain size decreased, thereby increasing the reaction rate and decreasing the response time. In addition, the ullage volume (void fraction) decreased when small, densely stacked catalyst grains were used, and this helped decrease the response time, particularly the pressure rise and decay times.

Effect of Reactor Volume (Granular Catalyst)

The apparent activity of the catalyst bed increases as the grain size decreases. Thus, a fairly small reactor can be designed to completely decompose a propellant with a known flow rate. The effect of reactor volume on catalyst activity was investigated by using the case 2-1 and 2-2 thrusters. The volume in the latter was half that in the former; with the latter thruster, H_2O_2 can be completely decomposed at a flow rate of 45 g/s.

Figure 4 shows the pressures and temperature determined from the first pulse. The response times in cases 2-2 and 2-1 were 14, 108, and 94 ms and 12, 114, and 106 ms, respectively. The pressure rise and decay times improved slightly when the reactor volume decreased. This is because the difference in the ullage volume of the two reactors was negligible, because the granular catalysts were used instead of pellet catalysts and the void fraction among catalyst grains in both thrusters was small.

These observations are significant for aerospace applications because, by decreasing the catalyst grain size, the size or weight of a thruster can be decreased, which is significant because small size/low weight is desirable in many aerospace systems.

The values of the response times for different reactors and catalyst sizes are listed in Table 2. The fastest response times were observed in case 2-2, in which the granular catalyst was used.

Conclusions

The catalyst size and several design parameters of thrusters have been shown to influence the response times of thrusters. Two catalysts of different sizes and three thrusters with different types of injectors and reactor volumes are considered, and the response times of the thrusters are studied.

The pulse response times of a thruster with a spray injector were slower than those of a thruster with a showerhead injector because the ullage volume in the former was larger; however, the distribution of propellant droplets was better in the spray injector than the showerhead injector. Therefore, the spray injector cannot be used for decreasing the response time. For this type of injector, the continuous operation mode is preferred over the pulse operation mode.

A decrease in the catalyst grain size also led to a decrease in the response times and had two positive effects: the void fraction among catalyst grains decreased and the apparent activity of the catalyst bed increased because of an increase in the effective surface areas caused by a decrease in the diffusion resistance of the catalyst grains.

The response time improved slightly when the catalytic reactor volume was decreased by 50%. The improvement was not significant because the resulting decrease in the ullage volume was very small.

In this study, MnO_2 was used as the representative active material to investigate the response time on thruster design effects. The

response time of a thruster may be further decreased by using an appropriate catalyst. Catalysts with an activity greater than that of MnO_2 , such as Pt, Ag, and MnO_2 mixed with various promoters, are expected to considerably improve the response characteristics of H_2O_2 monopropellant thrusters.

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