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100N급 H_2O_2 단일 추진제 로켓 엔진의 개발

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Development of 100N class H_2O_2 Mono-propellant Rocket Engine

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ABSTRACT

Considering the increase of interest in H_2O_2 as a rocket propellant, a test facility and a rocket engine have been developed to research in areas of H_2O_2 mono-propellant propulsion. A detailed design-study of a H_2O_2 mono-propellant rocket engine of 100-N thrust is presented. Several firings attempted in early stage had some problems with misfire and chamber pressure decrease. Low environmental temperature and impurities included in hydrogen peroxide were considered to be the reasons. Addressing these points resulted in successful firing of the rocket engine and obtained thrust about 100 ~ 107-N.

Key Words: Hydrogen peroxide propulsion, Mono-propellant Rocket

1. Introduction

In recent years, there has been a renewed interest in the use of hydrogen peroxide (H_2O_2) as an oxidizer in bipropellant liquid rocket engines as well as in hybrid rocket engines.[1-4] This renewed interest is because of the growing importance in using propellants of low toxicity and enhanced versatility. The use of H_2O_2 in rocket propulsion offers the versatility of operating the engine on a dual mode: a bipropellant mode (either as a bipropellant liquid engine or as a hybrid rocket engine) for a large thrust requirement and a mono-propellant mode for a small thrust application. A propulsion unit without a requirement for a separate ignition unit offers a higher system-reliability. H_2O_2 decomposes into a mixture of superheated steam and oxygen to a temperature of around 1000K. This leads to automatic ignition either with a liquid fuel in a bi-propellant engine or with a solid fuel in a hybrid-rocket engine. Thus, the versatility with the additional advantage of automatic ignition makes the "green" H_2O_2 an attractive oxidizer.

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2. Properties of Hydrogen Peroxide

Pure Use a anhydrous H_2O_2 is a colorless, syrupy liquid. It blisters the skin and has a metallic taste. H_2O_2 is manufactured in large amounts by the electrolysis of aqueous solutions of sulfuric acid or of potassium bisulfate. It is also prepared by the action of acid on other peroxides, such as those of sodium and barium. These industrial grades of H_2O_2 are concentration of 50% or less. But for rocket engines, H_2O_2 of concentration 90% and above is required and this is prepared using suitable distillation units.

Pure solutions of H_2O_2 are inherently very stable. When carefully purified and kept in clean non-reactive containers, the rate of decomposition is extremely slow. In general, the stability of very pure H_2O_2 increases with the concentration. The properties of H_2O_2 are given in Table 1.

3. Engine Design

For the present study a laboratory scale rocket engine is to be designed for a thrust of 100N. The engine uses H_2O_2 of >90% concentration. The thrusting time is to be in excess of 10 seconds. The nozzle entry stagnation pressure = 2 MPa and the nozzle pressure ratio = 15. The calculated theoretical-performance values for the engine are as given in Table 2.[5)]

Generally the quality factor for c^* (or c^* efficiency) is taken as 0.95 for bi-propellant liquid engines and solid propellant motors. Since the engine under consideration is a mono-propellant one and the quality of combustion is very much dependent on the catalyst, a conservative value of 0.90 is assumed for the quality factor. Therefore, estimated experimental c^*,

$$c^*_{\exp t} = 940 \times 0.9 = 846 \frac{m}{s} \qquad (1)$$

$$c_{T_{sealevel}} = 1.1338 + \frac{A_e}{A_t}\left(\frac{P_e}{P_{0n}} - \frac{P_a}{P_{0n}}\right) = 1.3808 \qquad (2)$$

Assuming a quality factor for the thrust coefficient as 0.95

$$\left(C_{T_{sealevel}}\right)_{\exp t} = 1.3117 \qquad (3)$$

$$\left(I_{sp_{sealevel}}\right)_{\exp t} = 1.3117 \times 846 = 1109.7 \frac{N-s}{kg} \qquad (4)$$

Propellant flow rate,

Table 1 Properties of hydrogen peroxide

Properties	Data
Heat of formation	-187.7 MJ/kgmol
Auto ignition temperature	90% : 483K(in air), 442K(in oxygen); 99% : 395K(in air or oxygen)
Vapor pressure	At 303K : 90% : 666 Pa ; 98% : 400 Pa ; 99% : 373 Pa
Boiling point	90% : 414K ; 98~99% : 422K
Melting point	90% : 261.5K ; 98% : 270.5K ; 99% : 271.5 K
Density	At 298K : 90% : 1387 kg/m^3 ; 98% : 1431 kg/m^3 99% : 1437 kg/m^3
Viscosity	Slightly above the viscosity of water(~ 0.00085 kg/m-s)
Incompatible materials	Dirt, Catalytic metals such as iron, copper, manganese, etc., organics,
Lead to violent reaction	cyanides and combustibles such as leather, wood, cotton, paper, oil, etc.

$$\dot{m}_p = \frac{100}{1109.7} = 0.09013\frac{kg}{s} \qquad (5)$$

An average mass-flux of 200kg/m^2-s is assumed for the engine. Therefore, the cross-sectional area of the catalyst bed,

$$A = 4.5063 \times 10^{-4} m^2 \qquad (6)$$
$$\Rightarrow D = 0.02395m\ (say, 25mm)$$

Combustion chamber temperature,

$$T_0 = 1029.4 \times \sqrt{0.9} = 976.6K \qquad (7)$$

Combustion chamber gas-density,

$$\rho = \frac{2 \times 10^6}{(8314.3/22.105) \times 976.6} = 5.445\frac{kg}{m^3} \qquad (8)$$

Combustion-chamber-gas velocity,

$$u = \frac{0.09013}{(\pi/4) \times 0.025^2 \times 5.445} = 33.72m/s \qquad (9)$$

Table 2 Theoretical rocket performance characteristics of the hydrogen peroxide engine assuming frozen composition

CHEMICAL FORMULA	WT FRACTION	ENERGY CAL/G-MOL	STATE	TEMP DEG K
FUEL H 2.00000 O 2.00000	0.900000	-44880.000	L	298.15
FUEL H 2.00000 O 1.00000	0.100000	-68317.400	L	298.15

	CHAMBER	THROAT	EXIT
p_0/p_e	1.0000	1.8188	15.000
$p(MPA)$	2.0	1.01	0.133
$T(K)$	1029.54	906.39	559.65
$\overline{m}(kg/kgmol)$	22.105	22.105	22.105
γ	1.2648	1.2764	1.3158
$\mu(kg/m-s) \times 10^{-4}$	0.42755	0.38113	0.23851
$c_p(J/kg-K)$	1796.6	1737.1	1567.1
PRANTL NUMBER	0.8256	0.8421	0.8880
A_e/A_t		1.0000	2.6713
$c^*(m/s)$		940	940
C_T^0		0.702	1.338
$I_{sp_{vac}}(N-s/kg)$		1176.5	1424.9
$I_{sp_{sealevel}}(N-s/kg)$		1128.9	1297.7
$u_e(m/s)$		659.7	1257.5

MOLE FRACTIONS

H2O	0.70757	O2	0.29243

PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

H; HO2; H2; H2O2; O; OH; O3; H2O(S); and H2O(L)

For the assumed residence time of 1.5ms, the catalyst-bed length,

$$L = 33.72 \times 0.0015 = 0.0506m \Rightarrow say\, 55m \qquad (10)$$

Injector Orifice

To effectively de-link the feed system from the engine, generally about 0.6MPa or 10 percent of the chamber pressure, whichever is higher, is provided at the propellant injector. Therefore, a pressure drop of 0.7MPa is provided for the propellant injection. For the mass flow-rate of *0.090 kg/s*, assuming the coefficient of discharge for the orifice as *0.8*, the orifice diameter is calculated as *1.8 mm*. As the variation of propellant-injection characteristics are to be considered for the study of engine performance, different orifice diameters from 1.4 mm to 2 mm in steps of 0.2 mm are selected.

Nozzle Dimensions

The mass flow-rate through the choked nozzle is given by,

$$\dot{m} = \frac{P_{0n} A_t}{C^*_{expt}} \qquad (11)$$

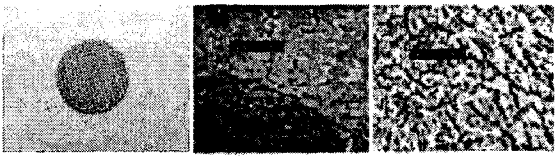
$$A_t = \frac{0.09013 \times 846}{2 \times 10^6} = 3.812 \times 10^{-5} m^2 \qquad (12)$$

$$D_e = \sqrt{2.6713} \times 7 = 11.44mm \Rightarrow say\ \ 12mm \qquad (13)$$

A half-cone angle of 13° is selected for the nozzle.

Catalyst Bed

For the decomposition of H_2O_2, catalysts are used and the catalyst systems are basically of three types: 1) liquid-liquid, 2) pellet bed, and 3) screen bed.[2, 3, 6)] The screen bed system is found to be the most effective one. There are two important parameters for the design of a screen bed: 1) the average mass flux through the bed (the so called bed-loading) and 2) the average residence time. Among the screen bed systems, pure silver screen is found to be most effective one. 20-mesh pure-silver screens were used for the catalyst bed The 20-mesh(0.356 mm Dia.) silver screen discs were activated with nitric acid and solution of samarium nitrate to enhance decomposition efficiency. Figure 1. shows surface condition of silver catalyst before and after activation. The total catalyst-bed length of 55mm was stacked with 120 silver screen discs and interposed with three perforated separator discs of stainless steel (each of 4mm thick). The total catalyst bed was compacted at 15 MPa. Adopted values of mass-flux in proven beds of silver screen vary from 117- to 280-kg/m^2-s.[6-9)] Average residence time in the catalyst bed varied from 0.7ms to 1.5ms.[13-16)]



Silver Screen Disc Before Activation After Activation

Fig. 1 Surface condition of silver catalyst

Propellant Tank Pressure

For the mass flux of 200 kg/m^2-s, the pressure drop across the catalyst bed is expected to be about 0.85 MPa.[6)] Therefore the pressure upstream of catalyst bed = 2.0+0.85= 2.85MPa. With the pressure drop of 0.7MPa across the injector orifice and 0.2MPa across the solenoid valve, the propellant tank pressure = 3.75MPa. A minimum pressure drop of 1.0MPa is to exist at the pressure regulator. Therefore, the minimum pressure upstream of the pressure regulator = 4.75MPa.

Propellant Tank Volume

Thrusting time is to be in excess of 10s. Assuming an ullage volume of 5 percent of propellant volume and 5 percent of propellant volume for tube-passages and protuberances, with a standard one liter tank available in the market, the propellant volume that can be stored in the tank,

$$V_p = \frac{10^{-3}}{1.1} = 9.091 \times 10^{-4} m^3 \qquad (14)$$

$say\ 0.9\ell$

Volume flow-rate of propellant for the engine of 100N thrust,

$$\dot{V}_p = \frac{0.09013}{1400} = 6.4379 \times 10^{-5} m^3/s \qquad (15)$$

Therefore the maximum-possible thrusting time,

$$t_{\max} = \frac{9.091 \times 10^{-4}}{6.4379 \times 10^{-5}} = 14.12s \qquad (16)$$

As it is not being envisaged to fix any anti-vortex unit at the outlet within the propellant tank, arbitrarily a time of 12s is fixed as the maximum rated thrusting time. Therefore with the initial propellant volume of 0.9 liter, maximum thrusting time is around 12 s.

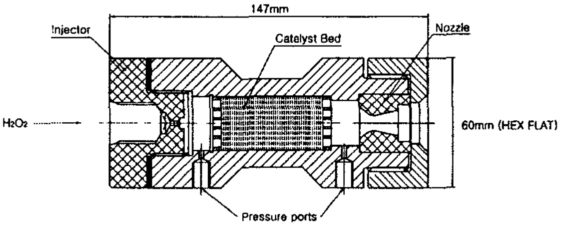


Fig. 2 Hydrogen peroxide engine of 100N thrust.

Table 3 Specifications of the H_2O_2 engine and its facility

Engine thrust	= 100 N
Estimated specific impulse	= 1110 N-s/kg
Regulated H_2O_2 tank pressure	= 3.75 MPa
Injector pressure drop	= 0.70 MPa
Injector orifice diameter	= 1.8 mm
Nozzle entry stagnation pressure	= 2.0 MPa
Propellant flow rate	= 0.090 kg/s
Catalyst bed-length	= 55mm
Approximate thrusting time	= 12 s
Nozzle throat diameter	= 7 mm
Nozzle exit diameter	= 12 mm

The assembly drawing of engine that has been fabricated is shown in Fig. 2. The specifications of the engine are given in Table 3.

Hydrogen Peroxide Distillation Unit

Possibly the main impediment in starting the H_2O_2 based rocket research is the difficulty in getting the rocket grade H_2O_2, say 90 %or more of concentration. To solve this problem, a distillation unit has been realized and this is shown in Fig. 3. The distillation unit is evacuated to a pressure of about 100mm of mercury and the evaporating flask is heated to a temperature around 70°C.

Test Facility

The sketch of the realized facility of the H_2O_2 engine is shown in Fig. 3. Sufficient safety features have been incorporated by introducing burst diaphragm and relief valve in the test facility. All the control valves are remotely operated. As the pressure regulator of low flow capacity required for the 100N engine was prohibitively expensive, a pressure regulator of high flow capacity (c_v = 0.06) had to be selected and this was made suitable for the 100N engine by adding a bypass orifice.[7] Pressure transducers are fitted at five stations: *pressurization tank, propellant tank, upstream of the injector, chamber pressure upstream of the catalyst bed, and downstream of the catalyst bed.*

Propellant is filled into the 1000 cc tank through quick connectors. Pressure regulator is set to the required propellant tank pressure. Recording and display of the pressure transducer-readings are initiated. Nitrogen supply is opened and it enters the gas pressurization tank of 1000cc volume after passing through 40 and 7 micron filters. Once the propellant tank pressure is stabilized, shut-off valve is opened to initiate the engine operation. The engine is fired until the propellant is consumed (~12s for 900cc of propellant). Once the propellant is consumed nitrogen-purging automatically follows to cool the engine.

In order to gain experience in the operation of the facility and also to prove the system, the facility has been tested extensively under simulated condition using water or nitrogen. While using nitrogen, the injector orifice and nozzle throat diameters were altered to simulate the engine operation. A typical recording of the simulated test using nitrogen is given in Fig. 4.

Hot Test

Several attempts to fire the engine was not successful in initial stage. A typical failed-test result is shown in Fig. 5. Only pulsed decompositions (at ~3.4 s and ~4.9s) could be obtained. The possible reasons for the H_2O_2 not getting decomposed at the catalyst bed could be two. The first could be the low environmental temperature. At the time of the test the atmospheric temperature was around 5°C. Wllis[8] reported the the most pronounced effect of engine case temperature on starting-time delays and most

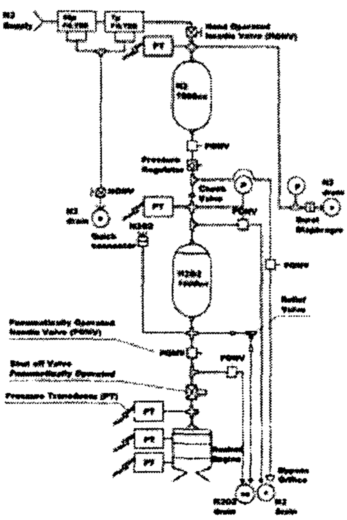


Fig. 3 Hydrogen peroxide rocket engine facility

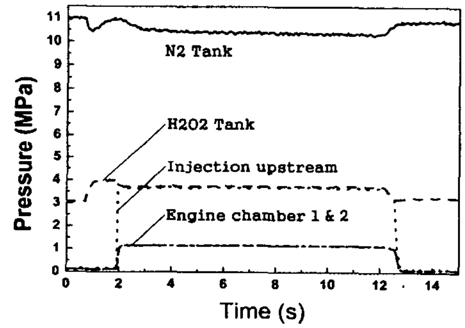


Fig. 4 Engine pressure-recordings of a simulated test using nitrogen.

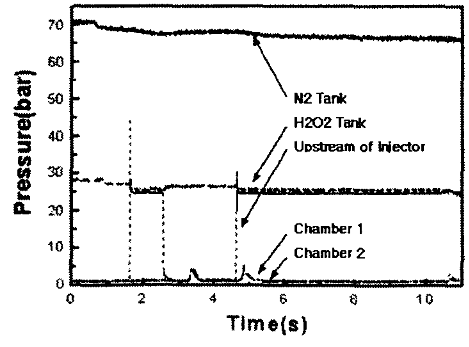


Fig. 5 Pressure time traces of a hot test that failed.

of his tests were conducted at the case temperature of 200°C. Love and Stillwell[9] maintained the propellant tank at a temperature around 30°C. The second possibility is the insufficient surface contact of the catalyst material with the H_2O_2. In the initial tests 20 mesh silver screens were used. Runckel et al.[10] found 40 mesh silver screens to be better than 20 mesh silver screens.

As the developmental activity, the propellant tank was jacketed with heater elements and maintained at 35°C. The engine case was also jacketed with heater elements and maintained at a temperature of 60°C. In order to increase the surface area of the catalyst screens, the catalyst pack was compacted at 35MPa. The hot tests with these modifications were conducted. Initially the engine was successfully fired and the chamber pressure was build up to expected value. But the engine chamber pressure was decreased with the increase of the numbers of engine fire. The recording data from the first fire to the third fire are shown in Fig 6, Fig 7, and Fig 8.

The possible reason for the decrease chamber pressure could be the impurities included in the concentrated H_2O_2. The infinitesimal amount of impurities included in H_2O_2 could be hindered decomposition of H_2O_2. Whitehead[11] explains the importance of reducing the impurities in preparing a propellant grade concentrated H_2O_2. To reduce the impurities in concentrated H_2O_2, a rotary evaporator has been used. The concentrated 90% of H_2O_2, acquired by former distillation unit, was purified through evaporation and condensation process by the rotary evaporator.

As the next developmental activity, the hot tests were conducted with purified H_2O_2 of 90% concentration. The propellant tank was maintained at 50°C and the engine case was maintained the atmospheric temperature (around

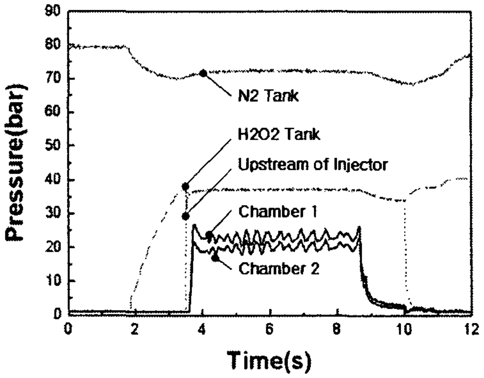


Fig. 6 Pressuretime traces of hot testes with Unpurified H_2O_2(Tp : 35 °C , Te : 60 °C, 1st Fire)

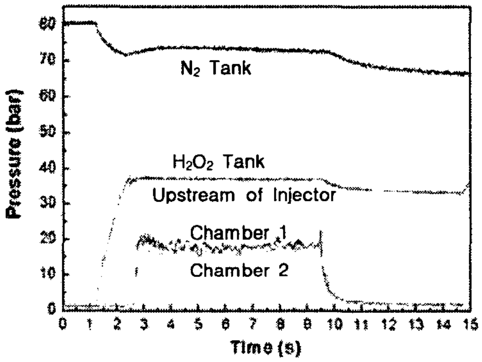


Fig. 7 Pressuretime traces of hot testes with Unpurified H_2O_2(Tp : 35 °C , Te : 60 °C, 2nd Fire)

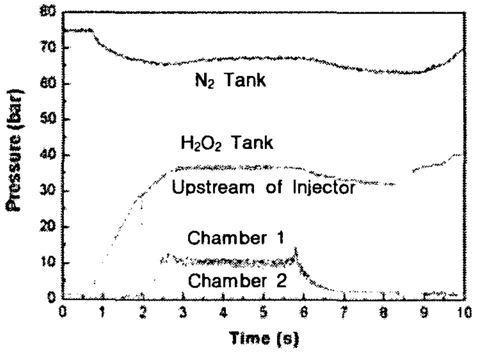


Fig. 8 Pressuretime traces of hot testes with Unpurified H_2O_2(Tp : 35 °C , Te : 60 °C, 3rd Fire)

12 °C). The problem of decrease chamber pressure was resolved with purified H_2O_2. The test result using purified H_2O_2 is shown in Fig 9. The test consisted of injected concentrated H_2O_2 for two intervals with a gap of about 3 seconds: the first for about 4.4 s, (from ~2.3th s to ~ 6.7ths, Fig. 9) and the second for more than 4 seconds (from ~9.9th s onwards, Fig. 9).

Each two injection periods, the engine was successfully fired and the chamber pressure was built up to expected values. At the first injection period, the pressure rising time was retarded about 2.5 seconds and the chamber 2 pressure risen up to 20.5 bars. At the second injection period, the chamber pressure was risen up as soon as the injection was started and the chamber 2 pressure risen up to 22.5 bars. The reason for retardation of pressure rising and lower chamber pressure during the first injection could be low temperature of engine case.

In case of successful fires, the thrust was calculated with the formulas used in engine design and obtained about 100~107-N.

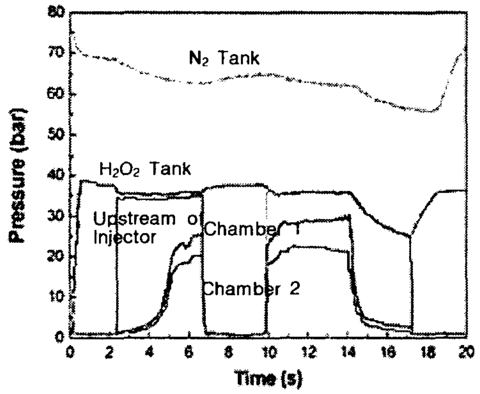


Fig. 9 Pressure time traces of hot testes with purified H_2O_2(Tp : 50 °C, Te : 12 °C, 3rd Fire)

Conclusions

Considering the importance of this "green" and versatile H_2O_2, it has been planned to develop a laboratory scale test facility and a rocket engine for research in the areas of H_2O_2 propulsion.

The detailed design of a 100-N thrust class engine and facility of the H_2O_2 mono-propellant has been presented. Hot tests revealed the needs to have a controlled high temperature environment for engine and propellant. The modifications were incorporated to enhanced temperature for the propellant and engine case. Though these modifications yielded successful firing of the engine, the engine chamber pressure shown decrease tendency with the increase of the engine firing times. High purity of H_2O_2 resolved the decrease tendency of engine chamber pressure. Finally the thrust was obtained about 100~107-N as expected.

Further tests to understand the effects of environmental temperature, catalyst characteristic and injector are in progress.

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