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산화제 과잉 예연소기 저주파 연소특성 연구

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Research on the Low-Frequency Combustion Characteristics of an Oxygen-Rich Preburner

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ABSTRACT

Combustion pressures were measured to study combustion stability for an oxygen rich preburner by both of static and dynamic pressure sensors. The resolutions of each static and dynamic pressure sensor are the 1,000 Hz and 25,600 Hz, respectively. The nominal combustion pressure of the preburner was 200 bar but 80 bar was used at the several initial tests for the safety reason. Two stage ignition was applied to reduce the ignition impact for every tests including the tests with 200 bar combustion pressure. The tests lasted for 10 sec. max. and a little fluctuations of pressure was observed during the main mode. The measured pressures were studied by FFT analysis and no noticeable frequency coupling was found. Thus the preburner can be regarded as stable and it can be utilized for further study on staged combustion cycle liquid rocket engine.

초 록

산화제 과잉 예연소기의 연소안정성을 알아보기 위하여 예연소기의 각 부위에서 압력을 측정하였다. 압력측정은 정압센서와 동압센서를 모두 이용하여 이루어졌다. 이 때 사용된 정압센서와 동압센서의 해상도는 각각 최고 1000 Hz와 25,600 Hz이다. 예연소기의 정격압은 200 bar이나 위험을 줄이기 위하여 초기에는 80 bar로 낮추어 시험을 하였고 안정성이 확인된 이후 200 bar 시험을 실시하였다. 또한 모든 시험에서 점화충격을 줄이기 위하여 저압점화 후 연소압을 정격압력까지 올리는 2단 점화를 사용하였다. 시험은 최대 약 10초가량 실시되었으며 메인모드 진입 이후에는 연소압에 큰 변화 보이지 않았다. 연소압의 측정결과는 FFT를 통해 좀 더 심도 있게 분석되었으며 그 결과 예연소기의 연소안정성을 해할 만한 주파수의 커플링은 발견되지 않았다. 따라서 현재 개발되고 있는 예연소기는 향후 다단 연소사이클 엔진 연구에 활용할 수 있을 것으로 기대한다.

Key Words: Preburner(예연소기), Liquid Rocket Engine(액체로켓엔진), LOx(액체산소), Oxygen Rich Combustuion(산화제 과잉 연소), Lean burn(희박연소)

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1. Introduction

A preburner is one of the key components of staged combustion liquid rocket engines. The development of oxygen rich preburner is notoriously hard challenges because of the difficulties dealing with hot oxygen gas. In fact, oxygen rich combustion, so called lean combustion, is getting more and more attention in the field of gas burners and turbines because of NOx control[1, 2]. However, a preburner of rocket engine is very different from conventional burners in the characteristics of combustion. The equivalence ratio of the preburner is 0.226 that is much more less than that of conventional gas burners. On the other hand, the mass flow rate and injector swirl number of the preburner are much larger.

In order to study the extreme oxygen rich combustion, several hot fire tests were conducted with preburners. Initially the O/F ratio in the primary combustion zone is about 15 and increases up to 60 to lower the temperature of exhaust gas by additional oxidizer injected from the center holes located at the middle of the combustion chamber wall. The pressures measured during the tests were studied by FFT analysis. Dominant low frequency oscillation and its harmonics were observed from the static pressure sensors. There were many attempts to explain the low frequency harmonics such as vortex break down, precession of the vortex core and so on[3, 4]. However as stated earlier this theories can be hardly applied to the rocket engines.

The dynamic pressure sensors also provided information of pressure oscillation. Sometimes many higher dominant frequencies were observed with the dynamic sensors. However, in this papers, the frequencies up to 1,000 Hz was mainly investigated.

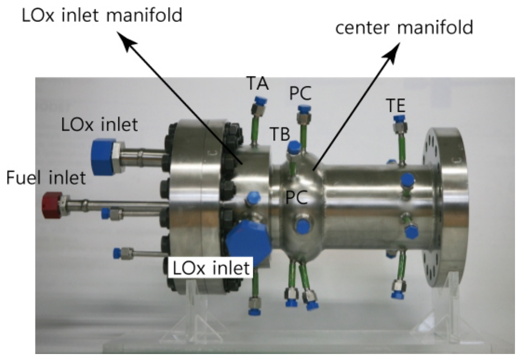

Fig. 1 Sensor location

2. Structure of the preburner and hot fire test

The tested preburner is so called a separable type, in which a mixing head and a combustion chamber can be divided. Thus, there are two LOx inlet ports; one for the mixing head and the other for the cooling channel. Since the mixing head takes all the fuel, only one fuel inlet is necessary. Refer the [3, 4] for the detailed description of the preburner.

Many static pressure sensors along with dynamic sensors and thermocouples were installed to monitor the combustion tests. Fig. 1 shows the locations and the abbreviation of the sensors. In Fig. 1 the capital letters T and P mean a thermocouple and a pressure sensor, respectively. The next letter A to E indicate the longitudinal locations. For example, PC means that the pressure sensor installed at the center manifold. Point F is not shown in the Fig. 1. It is located on the straight part between preburner and nozzle.

The fuel dynamic pressure sensor was installed on the top of mixing head and the oxidizer dynamic preassure sensor was located at the oxidizer center manifold.

A series of hot fire tests were conducted not only with nominal condition, but also with

Fig. 2 Hot fire test

Table 1. Test condition for reduced combustion pressure condition

		Aux. mode		Main mode	
		head	channel	head	channel
Mass flow [kg/sec]	LOx	2.10	6.63	3.48	10.75
	kerosene	0.130	-	0.240	-
Pressure [MPa]	LOx	5.63	5.04	9.91	8.77
	kerosene	6.48	-	9.68	-
Time [sec]		6.6 - 8		10 - 16	

reduced combustion pressure conditions. Even though the designed nominal combustion pressure is 200 bar, the reduced pressure of 80 bar was used for the safety cause for initial approaches. The lower combustion pressure was realized by the nozzle of larger throat diameter with the same mass flow rate. One of the test condition for reduced pressure condition and its result are shown in Table 1 and Fig. 3.

Figure 2 shows a typical hot fire test. The exhaust gas in the picture is almost transparent because the exhaust gas is virtually pure oxygen with little amount of CO_2 and H_2O[7].

Figure 3 shows the responses of the static pressure sensors from the low and the nominal pressure tests. The time (x axis) of the graph is relative not absolute. The data aquisition rate, f_s is 1,000 Hz, or time interval, Δt is 1/1000 sec.

In Fig. 3 at the reduced combustion pressure test, it is shown that the test was performed with two steps. The first low

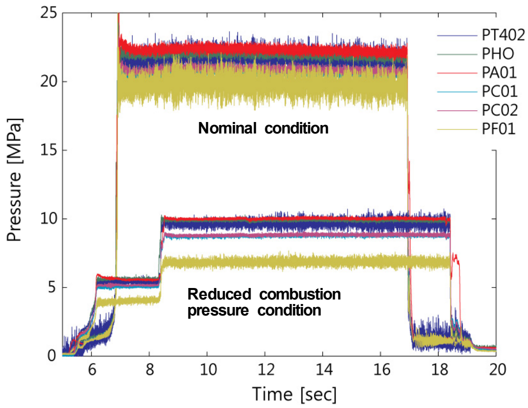

Fig. 3 Pressure of the various locations, PT402: kerosene inlet, PHO: LOx head inlet, PA01, LOx channel inlet manifold and PC01, PC02: LOx pressure in the center manifold

combustion pressure region from 6 sec to 8 sec called an auxiliary mode was prepared for smooth pressure development inside the chamber. The second higher pressure zone is called a main mode in which nominal mass flow rate was used. A similar experiment was conducted by Haeseler et. al.[8] and their combustion pressure reached to 122.5 bar with a subscale engine.

Unlike the lower plot in Fig. 3, no peculiar aux. mode was shown for the high pressure test (nominal condition), because the ignition sequence was adjusted not to have constant aux. mode. However, for the most of high pressure tests auxiliary modes lasted for 2 to 3 sec. as well.

3. FFT analysis of main combustion zone

In Fig. 4 FFT analysis was introduced to study the pressure oscillation in the main mode of reduced combustion pressure condition. The number of the total sample, N is more than 8,000 and the sampling frequency, f_s is 1,000 Hz. The fundamental frequency, f_o that is defined by Eq. 1 and the Nyquist frequency, f_N are 0.0563 Hz and 500 Hz, respectively.

$$f_o = \frac{f_s}{N} \tag{1}$$

Amplitude spectrum of the FFT result was evaluated as shown in Eq. 2.

$$\begin{aligned} Y(f) &= FFT\{y(t)\} \\ A_i &= 2\sqrt{Y(f_i)\,Y(f_i)^*} \end{aligned} \tag{2}$$

where y(t) is any function of time, Y(f) is FFT of y(t) and A_i is amplitude spectrum.

Figure 4 shows the dominant frequency at the each location of preburner with combustion pressure of 80 bar. It is noticed that the combustion pressure(PF01) has the harmonic frequencies of 60, 180, 300 Hz and so on. The magnitudes of the frequencies decrease as the frequency increases. The dominant frequencies does not seem to have any special relationship between the locations.

Figure 5 is the same plot as Fig. 4 but the combustion pressure is 200 bar(nominal condition). It shows that the dominant frequency of 60 Hz disappeared. Instead it was shifted to 81 Hz.

Even though low frequency oscillations with harmonics were observed, their amplitudes are generally less than 1% in comparison with combustion pressures.

The time resolution of dynamic pressure measurement, Δt is 3.90625×10^{-5} sec and the sample rate, f_s is 25,600 Hz. The Nyquist frequency, f_N is 12,800 Hz. Fig. 6 is a FFT plot with narrowed frequency range up to 500 Hz.

In Fig. 6 the results from the dynamic pressure sensors show that the dominant harmonics of Fig. 4 seem to turn out the minor frequencies. Fig. 7 is a fully expanded plot. It shows some peculiar high frequencies. Once they might be considered to give bad influence to the combustion. However they disappeared in the high pressure test (Fig. 8).

It would be supposed that high pressure condition increased damping capacity of combustion gas[12] and lessened discontinuity of thermal properties under supercritical condition[13]. Like the results from static sensors the amplitudes acquired from dynamic sensors are also less than 1% in all frequency range.

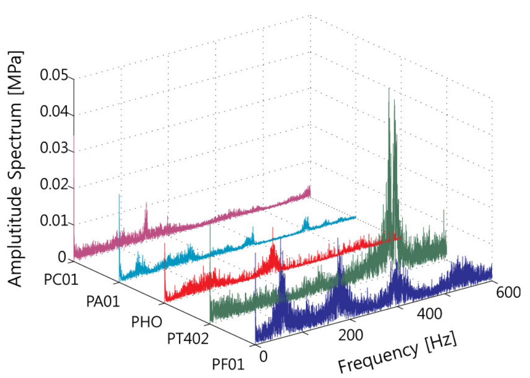

Fig. 4 FFT results of the pressures of the main mode (80 bar)

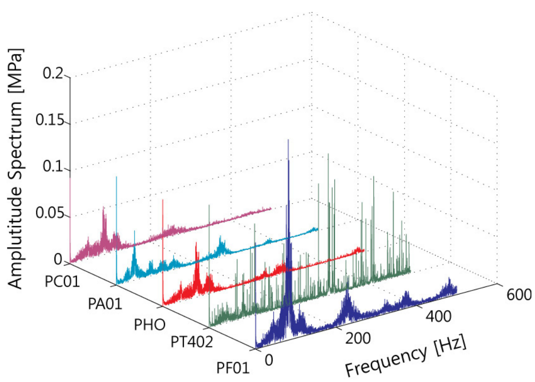

Fig. 5 FFT results of the pressures of the main mode (200 bar)

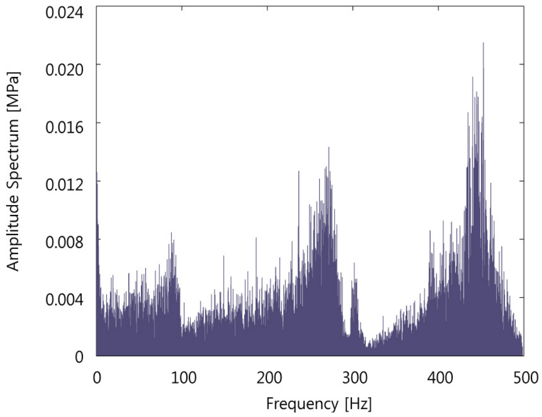

Fig. 6 FFT results of the dynamic pressures of the main mode (80 bar) with reduced span

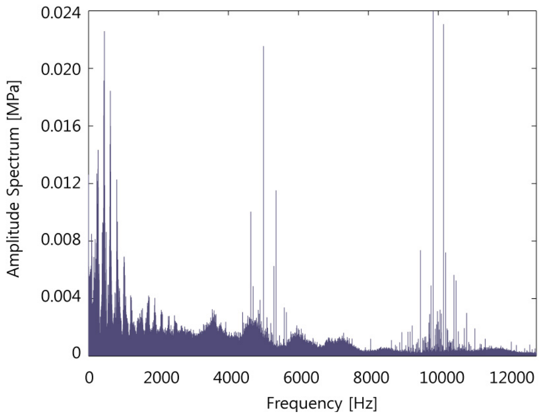

Fig. 7 FFT results of the dynamic pressures of the main mode (80 bar)

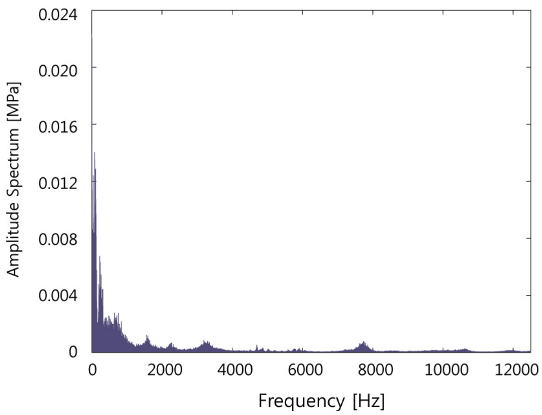

Fig. 8 FFT results of the dynamic pressures of the main mode (200 bar)

Low frequency pressure oscillation might be induced by the disturbance from hydraulic resistance not only in propellant supply system, but also in mixing head, such as manifolds, injectors and so on. In addition, the behaviors of pressure regulators, turbopump and internal shapes of orifices, shut-off valves, feeding lines could also excite low frequency oscillation. In other words, such phenomena always exist during combustion tests, and if they are not properly damped out, it could be drastically amplified by combustion energy in combustion chamber. Howver during hot fire tests practically, it is very hard to find out where is the primary location leading low-frequency oscillation and how to reduce its magnitude, so many research works focused on how to increase damping capability against oscillation.

In our case, it is also very difficult to explain the low frequency harmonics because the results are very inconsistent. However, one thing clear is that the low frequency harmonics exist.

There was some researches that may analyze the low frequency harmonics. One of the prominent explanation is the oscillation of O/F ratio. According to the classification proposed by Krebes et al.[9], the low frequency harmonics 60 to 80 Hz is located in the intermediated - frequency instabilities (50~1000 Hz) usually correspondent to the longitudinal acoustic modes of the combustor. Mongia et al.[10] proposed that the frequencies within this range were related to the coupling between the O/F ratio and oscillations. Therefore the natural frequency of the combustion chamber was calculated to be compared the low frequency. However, the computed 480 Hz was not close enough to the 100 Hz. It may rather explain around the 450

Hz frequency shown in Fig 6.

As the second approach, tangential motion was studied even though Krebes et al.[8] classified that this motion was related to the high frequency instability (>1000 Hz). Cassidy and Falvey [11] made a correlation between the angular momentum and the frequency by using a hot film anemometer and a pressure cell. The correlation showed that the frequency parameter, $\frac{fD^3}{Q}$ is proportional to the Strouhal number, $\frac{fD}{u}$ where f is the frequency, D is the diameter, Q is the volume flowrate, Ω is the flux of the angular momentum and u is the axial velocity. However, when the Strouhal number was small enough, $\frac{fD^3}{Q}$ did not seem to change much but to remain constant. The minimum value of the, $\frac{fD^3}{Q}$ lies between 0.8 to 0.9.

Since it is believed that the axial velocity is the only dominant velocity component of the gas in the combustion chamber, Strouhal number of the gas should be very small. Thus taking the min. number of the $\frac{fD^3}{Q}$, 0.85 [11] the frequency can be calculated 338.9 Hz.

This estimated frequency, 338.9 Hz is very subtle to make a conclusion that the vortex break down is responsible for the detected low frequency. The value is not close enough to the detected frequency, even though many simplifications were applied to the problem. In addition, Fig. 5 shows that there are frequency peaks from 380 to 400 Hz and no such frequency is shown in Fig. 6. Therefore, the angular motion with min. $\frac{fD^3}{Q}$ value may not match this frequency region. However, this is very crude conclusion with not sufficient number of experiments.

Ha, et. al[12] studied the low frequency dynamics of the LRE combustion chamber. They found that the time delay of propellants for combustion affected the combustion stability. The longer the delay time, the less the combustion stability. Ha, et. al[12] estimated the low frequency instability of 164 Hz.

It was not easy to clarify the low frequency harmonics, the detected frequency did not affect the combustion in detrimental way and the combustion itself was very stable. In addition the combustion looked more stable with higher combustion pressure.

4. Conclusion

A preburner in which oxygen rich combustion occurs was designed and tested for the future liquid rocket engine development. The nominal combustion pressure and O/F ratio are 200 bar and 60, respectively. The tests were carried out with various sensors such as dynamic and static pressure sensors, thermocouples and so on. The static pressure sensors detected low frequency pressure fluctuation and the results were compared with those of the dynamic pressure sensors. Both kinds of the sensors showed low frequency harmonics and the causes of low frequency harmonics were yet clearly defined. However, no frequency seems to affect to combustion and to be coupled with the acoustics of the preburners. Therefore, in the practical point of view, the preburner developed under this oxidizer-rich combustion program can be used as a component for power pack tests of staged-combustion cycle development program.

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