다종의 동축 스월형 단일 분사기 연소 특성에 관한 실험적 연구

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Study on Combustion Characteristics of Unielement Thrust Chambers with Various Injectors

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ABSTRACT

Experimental study on combustion characteristics of double swirl coaxial injectors has been conducted for the assessment of critical injector design parameters. A reusable, unielement thrust chamber has been fabricated with a water-cooled copper nozzle. Two principal design parameters, a swirl angle and a recess length, have been investigated through hot firing tests for the understanding of their effects on high pressure combustion. Clearly, both parameters considerably affect the combustion efficiency, dynamics and hydraulic characteristics of an injector. Internal mixing of propellants in a recess region increases combustion efficiency along with the increase of a pressure drop required for flowing the same amount of mass flow rates. It is concluded that pressure buildup due to flame can be released by the increase of LOx flow axial momentum or the reduction of a recess length. Dynamic pressure measurements of the thrust chamber show varied dynamic behaviors depending on injector configurations.

초 록

본 연구에서는 이중 와류 동축형 분사기의 설계 인자 특성 파악을 위해 실 추진제 연소 시험을 수행하였다. 본 시험에서는 물냉각이 적용된 재사용이 가능한 구리 재질의 노즐을 사용하였다. 연소 시험 시 고압 연소 조건에서 주요 설계 변수인 분무각과 함몰길이의 영향을 살펴보았다. 이 두 변수는 분사기의 연소 성능과 동특성, 수력학적인 특성에 큰 영향을 미치고 있다. 함몰영역에서의 내부혼합은 같은 유량을 보내기 위해 필요한 차압의 증가와 더불어 연소 효율을 증가시킨다. 내부 화염에 의한 분사기 차압은 LOx 축 방향 모멘텀 및 함몰길이의 변경을 통해 감소 또는 증가됨을 알 수 있었다. 또한 연소기에서 발생하는 동압 특성은 분사기의 형상에 따라 변화함을 알 수 있었다.

Key Words: Swirl Coaxial Injector(와류 동축 분사기), Subscale Combustion Test(축소형 시험)

INTRODUCTION

For the development of a Liquid Rocket Engine (LRE) thrust chamber, the design of

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Nomenclature

P_d = Pressure drop
d_{nozzle} = Nozzle diameter
n_o = Number of the holes
L = Recess length
C_d = Discharge coefficients = $\dot{m}/(A_o\sqrt{2\rho P_d})$
R.N = Recess number, the length ratio of a total recess to an impinging point
2α = Spray angle
Φ = Filling coefficients
d_o = Diameter of the holes

an injector becomes one of critical tasks in terms not only of engine efficiencies but of functionalities of an engine. A LRE thrust chamber has relatively high energy density compared with other conventional combustion devices, which results in harsh physical environments in a combustion chamber with high temperature and pressure. For the optimum design of the components of a LRE surviving in severe thermal and structural loads, many design issues and concerns come to be put on designers' working table. For example, one has to consider mechanical and physical properties of material for an application, flow analysis, thermal load distribution, combustion stability, efficiency and so on. These design parameters closely correlate with each other and thus, the present knowledge on the issues is far from perfection.

As mentioned, an injector that delivers fuel and oxidizer into a combustion chamber by expense of potential energy of propellants significantly affects the efficiency and function of a LRE. Thus, a LRE injector provides mixing of propellants and eventually affects the combustion efficiency and stability. It is more than necessary to understand characteristics of the design parameters in detail for the optimization of its function and performance at high temperature and pressure conditions. At the early stage of the injector development, significant numbers of design parameters have to be considered first and eventually, the preliminary design leads to the detailed configurations of couples of injectors. Injector designs resulted from the preliminary study need to be examined through a number of tests for the assessment of their characteristics in reacting flow even though cold flow tests are usually scheduled to be conducted before any hot firing tests.

One of common driving factors at the present day is cost for the development of any challenging scientific and engineering devices. A LRE cannot be an exception for this. Therefore, it is financially impossible to fabricate each fullscale thrust chamber for every injector candidate and to conduct a series of combustion tests. Moreover, an aggressive development schedule does not usually grant to research engineers a right to acquire all the data from fullscale combustion tests with various injector configurations. For these reasons, a number of fullscale tests should be minimized and one or two variations in the injector design would be acceptable for the fabrication and the combustion tests of fullscale thrust chambers. Besides economical and schedule reasons mentioned so far, subscale thrust chamber tests are often planned to accumulate experimental data through combustion tests of various injector parameters and to study their effects on each other. These kinds of subscale firing tests have been exercised by many previous developers in this field and are regarded as successful ones even without pointing out that the combustion environments in subscale chambers do not exactly mirror the actual situations occurring in fullscale ones[1,2]. The simplest one among subscale tests becomes a unielement chamber without any additional or auxiliary flow injection except propellant flows through a single injector. A unielement test has its strong advantages in providing data about characteristics of flame holding and hydraulics with actual propellants not to mention that it can also provide a plenty of information of combustion in shorter period and with lower cost than cases of multi-element and fullscale tests.

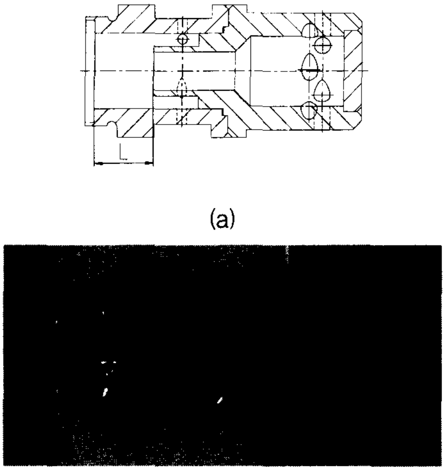
Most of published reports about unielement combustion tests, available on public domain, are authored by researchers of the United States, Europe, and Japan. For coaxial injectors, they provide test results of coaxial shear or coaxial swirl injectors with hydrogen/oxygen combination. At the beginning of the application, experimental data acquired from tests were lumped property of combustion such as chamber and manifold pressure and temperature. However, these days, the rapid development of non-intrusive measurement techniques allows researchers to investigate local physical events occurring in a combustion chamber. PDPA and Raman species measurements have been applied to the combustion of liquid oxygen and gaseous hydrogen[3].

In the present study, unielement combustion test results of double swirl coaxial injectors with various configurations are provided. Test results of double swirl injectors are barely known due to non accessibility to Russian research programs that had mainly utilized kerosene and liquid oxygen as propellants. Therefore, the present experimental results provide valuable data for the design of a high performance thrust chamber employing double swirl coaxial injectors with bi-liquid propellants. The following will present test devices used in the present study, results and discussion.

EXPERIMENTS

Injectors

Injectors used in liquid propellant thrust chambers can be generally categorized as impinging type, coaxial type and pintle type[4]. Impinging type injectors have been favored by LRE developers in the United States due to their relatively simple geometry and dynamics, which allow straightforward design and application. However, well-known combustion sensitive to instability of impinging injectors, especially to transverse velocity fluctuations, has been always a big problem during development. Meanwhile, coaxial type injectors would provide a better combustion stability with comparable combustion efficiency than impinging types when properly designed[5]. However, the dynamics of coaxial injectors are much more complicated and reveal bifurcation characteristics. Last, the pintle injectors have clear advantage over others in that engine thrust can be easily varied with them. However, none of pintle injectors has been applied to a booster or a sustainer level



(a)

(b)

Fig.1 (a) Cross sectional schematic of a double swirl coaxial injector(L a recess length)and (b)photographic view of an actual injector element

thrust chamber.

For the employment of liquid bi-propellants, impinging and coaxial type injectors can be applied to acquire maximum performance. Here in this study, the identification of combustion characteristics and dynamics of coaxial injectors was mainly purposed and thus, swirl is introduced for both liquid propellants for better atomization and mixing. The schematic drawing and picture of double swirl coaxial injectors fabricated for the study is presented in Fig. 1. Liquid oxygen enters the swirl chamber through tangential passages and kerosene (Jet A-1) does in the same swirling direction. Depending on the existence of a swirling chamber, an injector can be called "open" or "closed."

Injectors only with an oxidizer swirl chamber were applied in this study. As listed in Table 1, two different variations in a recess length and a swirl angle were tested. They are known as critical design factors affecting flame anchoring characteristics and combustion efficiency[6]. The same recess number, different swirl angle and filling coefficients, Φ, were assessed for their effects on combustion characteristics. The definition of the R.N. is the dimensionless value of the

Table 1. Design specifications of double swirl coaxial injectors tested in the present study

Injector	#11L	#11M	#14L	unit
P_d(LOx/Fuel)	10.4 / 10.4			bar
2α	80/120	65/120	80/120	deg
d_{nozzle}	5.3/9.7	4.45/8.45	5.3/9.7	mm
Φ	0.54/0.19	0.65/0.22	0.54/0.19	-
n_o	8/4			-
d_o	1.7/1.2	1.9/1.2	1.7/1.2	mm
L	5.4	6.3	1.6	mm
R.N	2		0.6	-

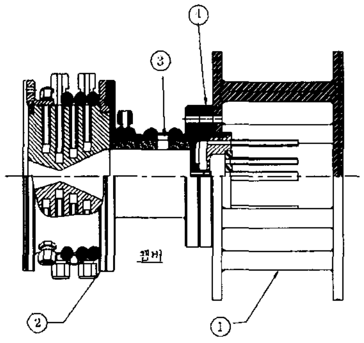


Fig. 2 Cross sectional view of a unielement thrust chamber : (1)test stand adapter (2)ater-cooled copper nozzle (3)cylindrical chamber (4)injector head

recess divided by the length where the inside liquid sheet meets the outside nozzle edge.

Table 2. General operating and design specification of a unielement thrust chamber

Item	Value	Unit
P_c	52.5	bar
O/F mass ratio	2.5	-
m_{ox}	289	g/s
m_f	116	g/s
C^*_{ideal}	1753	m/s
residence time	2.5	msec
C^* efficiency	94.5	%

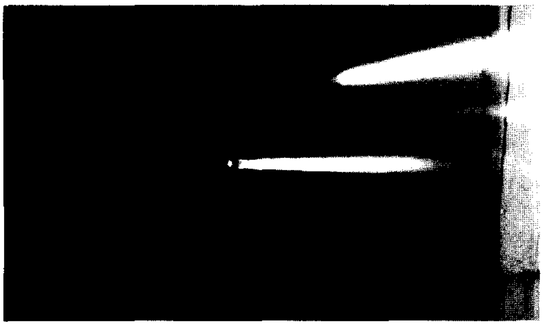


Fig. 3 Typical photographic view of a unielement thrust chamber under firing

Unielement Thrust Chamber

Cross sectional view of the unielement thrust chamber utilized in the study is provided in Fig. 2. The chamber consists of the injector head, the cylindrical chamber and the water-cooled nozzle. All the sections are bolted together and sealed with copper gaskets inserted between each section. For the test of different injector configurations, only the injector head needs to be changed and therefore, other chamber geometries are kept the same for all injectors. An injector element was brazed into the injector faceplate. The stainless steel cylindrical chamber was protected from excessive thermal load by a silica phenolic liner. A unique feature of the chamber is a water-cooled oxygen-free copper nozzle that allows the chamber to be reusable.

Dynamic and static pressures were measured at each injector manifold and chamber. Dynamic pressures are sampled at 50kHz and static property at 100Hz.

Operating Conditions

Unielement combustion tests usually lasted for three seconds in this study and this test duration allows the chamber to reach steady state at one fixed, constant condition. The ignition of the chamber was achieved by using a gaseous methane/oxygen torch. All the valve sequences of the combustion test were controlled by a preset PLC. Design values of operating conditions of the unielement thrust chamber are listed in Table 2.

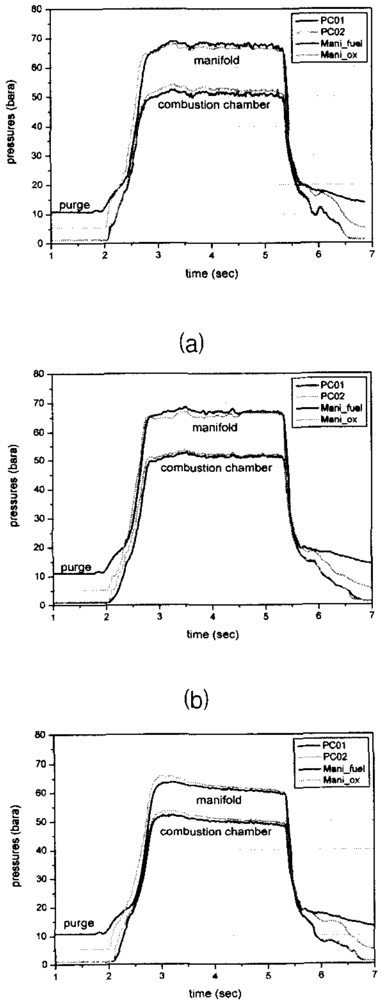
RESULTS AND DISCUSSIONS

Hydraulics of Injector

The combustion tests have been successfully conducted with a reusable copper nozzle and chamber pressures under combustion tests reached close to the design requirement slightly above the critical pressure of oxygen.

Figure 3 shows a photographic view of the thrust chamber under firing. As mentioned, a steady combustion condition typically lasted for three seconds that is long enough to allow the cooling nozzle to reach and stay at thermal balance. The combination of preset constant run tank pressures and appropriate cavitating venturies assures the introduction of constant mass flow rates of propellants into the combustion chamber regardless of manifold pressure increases.

The plots of static pressures at chamber and manifolds shown in Fig. 4 for each injector represent typical test results of constant thrust LRE's. Nitrogen purge before ignition resulted in initial pressure buildup in both manifolds and ignition starts at the moment of two-second on all the plots. Slow variations of the chamber pressure clearly follow the manifold pressure ones for all the cases. PC01 and PC02 in the plots both measure the chamber pressure in two different axial locations by 47 mm apart. PC01 measures upstream and PC02 does downstream close to the nozzle inlet. Larger values of PC02 than those of PC01 imply that the longitudinal dimension of the cylindrical chamber is considered not long enough to allow reaction to thoroughly occur in the chamber.



(a)

(b)

(c)

Fig. 4 Time traces of manifold and chamber pressure
(a) 11L ,(b) 11M and (c) 14L

Figure 5 shows summary of static pressure drop and increase for three different injectors. For the internal mixing cases, 11L and 11M, with a recess number of two, LOx film impinges on fuel film running on the inside surface of the fuel nozzle. A recess number of less than one indicates that LOx film would impinge on fuel film at the outside of the fuel nozzle. One clear observation in Fig. 5 is that a pressure drop across manifold and chamber under combustion becomes close to that under cold flow tests. This fact implies that flame would anchor at the initial mixing zone that locates in the recess region. Thus, the flame anchoring inside of the injector increases back pressure higher than the chamber pressure, which results in an overall increase of a pressure drop required for flowing a certain amount of propellants. The increase of a pressure drop at the fuel side seems to be more affected by flame anchoring compared with LOx side since fuel film flowing on the inner surface of the fuel nozzle has no extra room to release the pressure buildup. This argument becomes more favored looking at the external mixing case, 14L, where fuel film "sees" more space to expand into the chamber. The injector, 11M, with fuel and LOx nozzle diameters smaller than those of 11L provides similar values of a pressure drop with those of 11L, which indicates that an increase of axial momentum of LOx film pushing flame anchoring zone further downstream shows comparable effects on the reduction of a pressure drop with the enlargement of nozzle diameters and their gap.

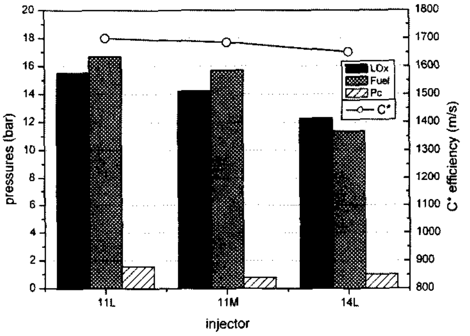


Fig. 5 Pressure drop across an injector head and chamber pressure increase for each injector, and its corresponding C* efficiency

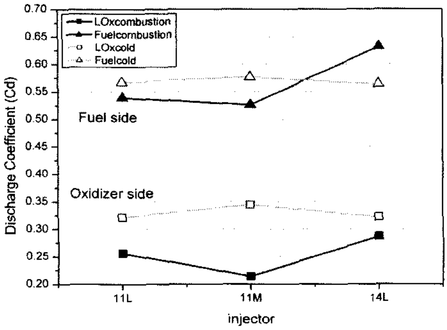


Fig. 6 Variations of discharge coefficients for each injector from cold flow and combustion tests

From these results, the location of flame anchoring zone becomes a dominant parameter in controlling a hydraulic pressure drop for double swirl coaxial injectors of these scales. The injector, 14L, with shorter mixing time than others seems to result in relatively poor combustion efficiency.

Discharge coefficients estimated for all the injectors under cold and hot test environments are given in Fig. 6. As argued from above, values of discharge coefficients at hot firing tests are less than those at cold flow tests. One thing worthy to note here is that for the external mixing case, 14L, a discharge coefficient of fuel under combustion becomes larger than that of cold flow due to sudden expansion of fuel flow before mixing with oxidizer flow.

Dynamics of Injector

Root-Mean-Square (RMS) values of dynamic pressures stand for a measure of power of pressure fluctuations. Fig. 7 shows RMS of dynamic pressures measured at all the manifold and chamber. General observations from the figure are that pressure

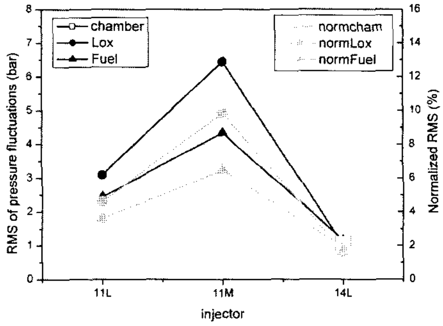
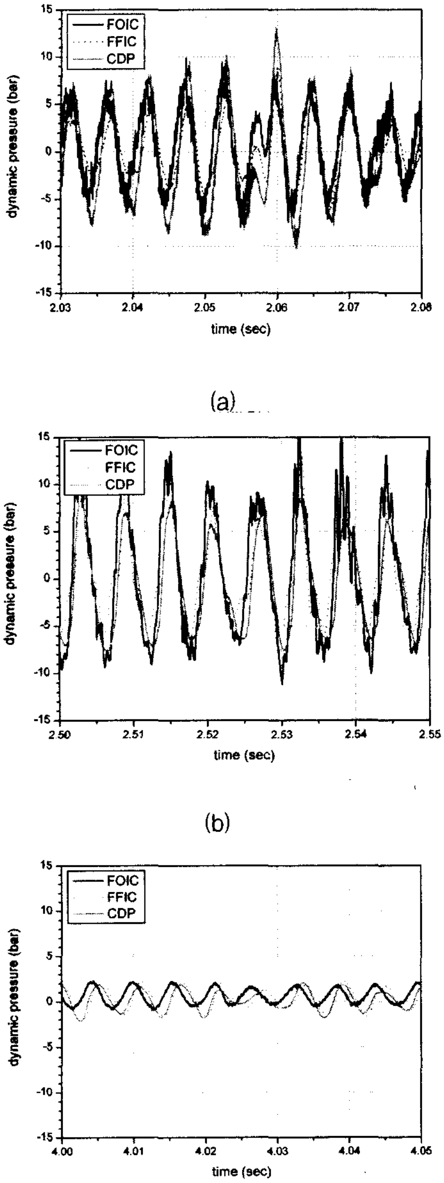


Fig. 7 Variations of RMS dynamic pressure fluctuations at steady conditions depending on the configuration of injectors

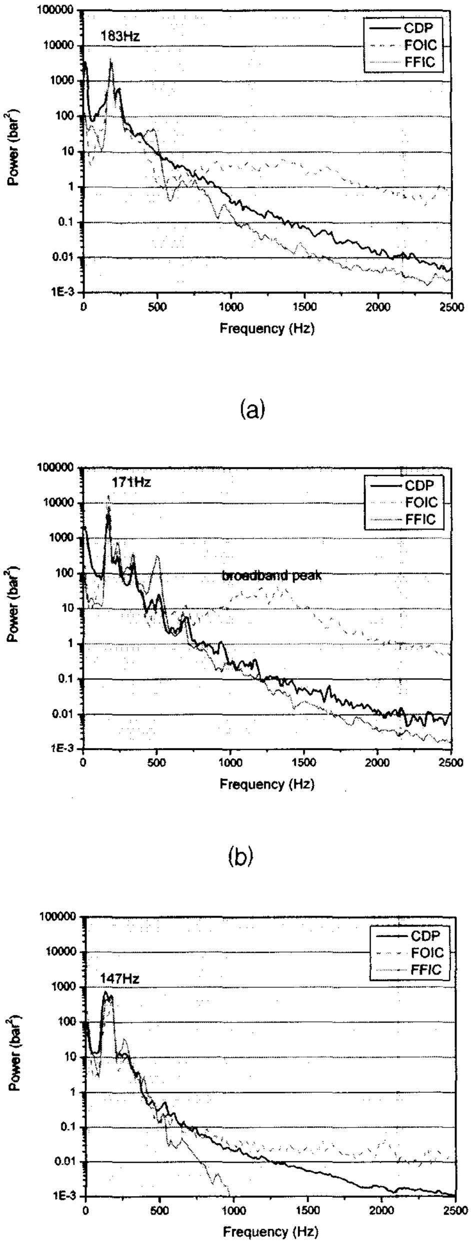


(a)

(b)

(c)

Fig. 8 Typical time traces of manifold and chamber dynamic pressures, (a) 11L, (b) 11M and (c) 14L (Compare amplitudes on the same vertical axis scale).



(a)

(b)

(c)

Fig. 9 Power spectrum plots of manifold and chamber dynamic pressures, (a)11L, (b)11M and (c) 14L fluctuates more vigorously for the internal mixing cases than for the external one, and that dynamic pressure fluctuations in the LOx manifold seem to be higher than those in the fuel manifold. Among two injectors, 11L and 11M, the pressure fluctuations larger for 11M are mainly due to larger filling coefficients.

Dynamic pressure traces in time are shown in Fig. 8 for all the cases. FOIC indicates pressure measurements at the LOx manifold, FFIC at the fuel and CDP at the chamber. Due to small dimensions of the present unielement thrust chamber, it is hardly possible for high-frequency resonant waves higher than 3000 Hz to be triggered and stand in the chamber. All the time plots in the figure indicate that there exist low-frequency waves in the chamber and manifold. For the internal mixing cases, 11L and 11M, dynamic pressure oscillations show typical nonlinear wave forms although pressure waves measured for 14L is much more like a sine wave. Another big difference between the internal and the external mixing cases is that relatively large and distinct phase delays are observed for the external case although phase differences clearly exist for the internal mixing injectors. This aspect of dynamic behavior of the injectors needs to be carefully investigated.

The power spectrum plots for corresponding time plots in Fig. 8 are presented in Fig. 9. As observed in the time plots, low frequency waves correspond to around 170 Hz. Since a frequency of a pressure wave is proportional to the square root of a medium temperature, the order of combustion efficiency from the highest to the lowest can be regarded as 11L, 11M and 14L from the results of Fig. 9. Interestingly, the pressure fluctuations in the LOx manifold for 11M reveal a broadband peak around 1000 Hz, which is known as very typical characteristics of nonlinear phenomena sometimes, called chaos[7].

SUMMARY

The experimental study on combustion characteristics of double swirl coaxial injectors has been successfully carried out using a reusable unielement thrust chamber. The following have been reached from the current results. Both design parameters, a swirl angle and a recess length, considerably affect the combustion efficiency, dynamics and hydraulic characteristics of an injector. A recess number of more than one, which allows internal mixing of propellants, promotes premixing to increase combustion efficiency along with the negative effect that an increased pressure drop is required for flowing the same amount of mass flow rates. It is concluded that pressure buildup due to flame can be eased by the increase of LOx flow axial momentum or the reduction of a recess length. Dynamic pressure measurements of the thrust chamber show quite different dynamic behaviors depending on injector configurations. Bulk type, low frequency pressure oscillations are observed to occur in the manifold and chamber for all the injectors. Maximum amplitudes of dynamic pressure fluctuations are measured for the test of the injector with large filling coefficients and internal mixing.

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