# Backhole as a New Geometric Parameter and Acoustic Damper for the Swirl Injector in Liquid Rocket Engine

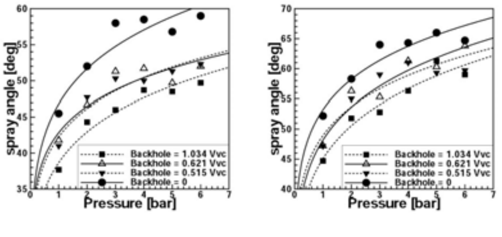
# 액체 로켓 엔진용 스월 인젝터를 위한 새로운 기하학적 변수이며 음향학적 감쇄자인 백홀에 대한 연구

## 1. 서론

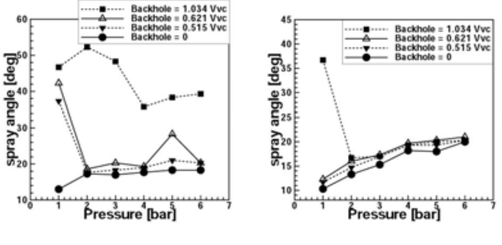
인젝터의 기하학적 형상이나 음향학적 특성이 연소에 직접적으로 영향을 줄 수 있다는 견해는 Bazarov 등에 의하여 꾸준히 제시되어 왔다. 실제로 러시아의 로켓 엔진에서는 배플(Baffle)이나 음향공(Cavity)없이 잘 설계된 인젝터만으로 연소불안정성을 억제하는 사례를 보여주고 있다. 이를 바탕으로 동축형 인젝터에서 내부 쪽에 위치하는 인젝터를 파동원이나 진동원으로 해석하려는 것은 그동안 러시아와 대만 등에서 시도되어 왔다. 그러나 이 경우에는 기체 상태로 분사되는 경우에 한정되었고 명확한 설계식이 제시되거나 연소불안정성의 제거기로서의 역할을 고찰한 것은 아니었다. 이에 본 연구에서는 스월 인젝터를 하나의 Resonator로 해석하여 연소불안정을 일으키게 한다고 여겨지는 연소실의 고유주파수 모드를 제거해주는 기능을 알아보고자 한다. 또한 스월 인젝터 고유의 분무 특성을 변화시키는 설계변수로서의 백홀을 연구하고자 한다. 이러한 연구는 향후 우리 나라의 고유 발사체인 KSLV의 연소불안정 없는 액체 로켓엔진 개발에도 크게 기여할 수 있으리라 예상된다.

## 2. 분무각의 조절

Fig. 1 (a), (b)와 같이 리세스가 없거나 얕을 때에는 백홀의 부피가 증가할 수록 분무각은 작아지는데 백홀이 없는 경우에 비해서 28%까지 감소하였다. 하지만 Fig. 1 (c), (d)와 같이 리세스를 깊게 둔 후 백홀의 부피를 바꾸어 가며 분무각을 측정해 보면, 백홀이 있는 경우에 분무각의 크기가 오히려 증가할 수도 있음을 알 수 있다. 이것은 백홀이 없는 경우에는 백홀의 부피가 큰 경우보다 산화제 유동의 각이 크고 리세스가 깊기 때문에 산화제 유동이 인젝터 밖으로 채 나오기 전에 연료 노즐 내벽에 부딪히면서 내벽을 타고 나오기 때문이다. 그러나 백홀의 부피가 충분히 크면 줄어든 산화제 유동의 각으로 인하여 유동이 연료 노즐 내벽에 닿지 않아서 간섭을 받지 않으므로 전체 분무각은 더 커지게 된다.



(a)No Recess (b)Recess = 2.50



(c)Recess = 3.00 (d)Recess = 3.25

Fig. 1 Spray angle of Swirl Injectors

### 3. 혼합효율에 대한 영향

너무 과도한 리세스나 너무 얕은 리세스는 혼합 효율에 악영향을 준다. 그러므로 산화제 노즐에서 나온 유동이 연료노즐의 끝단에 걸치도록 리세스를 조절하는 것이 혼합효율을 증가시킬 수 있는 방법이다. 그런데 백홀은 분무각을 보다 세밀하게 조절할 수 있다. 그러므로 백홀은 스월 인젝터가 여러 가지 다른 이유로 인하여 과도한 리세스를 가지도록 설계되었을 때, 산화제의 분무각을 조절하여 최적 혼합효율의 인젝터 설계가 가능하도록 한다.

Fig. 2의 혼합효율 그래프를 보면 부적절한 리세스를 가진다고 하더라도 백홀의 부피에 따라서 분무각이 조절되어 오히려 더 좋은 혼합특성을 나타내도록 할 수 있다는 것을 보여주고 있다. 또한 같은 리세스 조건이라도 백홀의 부피에 따라서 혼합효율이 변화하고 있음을 알 수 있다.

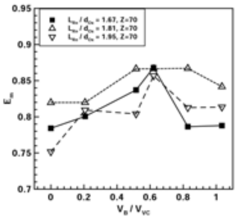


Fig. 2 Mixing Efficiency

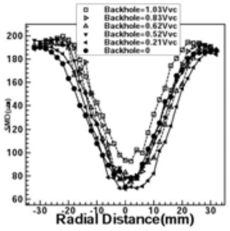


Fig.3 SMD

### 4. 미립화 특성에 대한 영향

백홀이 스월 인젝터에 존재하면 분무각이 줄어들고 단위시간당 유량이 증가하기 때문에 미립화에 불리할 것으로 예상할 수 있다. 단위시간당 유량이 증가할수록 SMD는 증가하므로, 백홀의 부피 증가에 따른 유량의 증가로 인하여 SMD는 증가해야 한다. 그러나 PDPA 결과인 Fig. 3를 보면 백홀의 부피가 와류실 부피의 20%정도가 되었을 때 평균적으로 가장 작은 SMD 값을 보이고 있었으며 백홀의 부피가 와류실 부피의 52% 수준이었을 때에도 백홀이 없는 경우와 비슷한 정도의 SMD 값을 나타내었다. 그러므로 백홀이 지나치게 큰 부피를 가지지 않는다면 스월 인젝터의 미립화 효율에 좋지 않은 영향을 준다고 통계적으로 단정하기 어렵다.

### 5. 단위시간당 유량의 증가

Fig. 4에서 백홀의 부피가 증가함에 따라서 산화제 유량이 15% 가량 증가하는 것을 알 수 있다. 일반적으로 유량계수 $\mu$는 다음과 같이 정의한다.

$$\dot{m} = \mu\pi(R^2 - R_i^2)\sqrt{2\rho\Delta P} \qquad (1)$$

그런데 압력강하($\Delta P$)와 밀도($\rho$)를 일정하게 유지하였으므로 단위시간당 유량 $\dot{m}$이 증가하기 위해서는 유동면적이나 유량계수 $\mu$가 증가할 수밖에 없다. 그리고 링 모양 유동의 최외각 반지름은 와류실의 내벽 반지름 $R$과 같다. 그러므로 유동면적이 증가하려면 링 모양 유동의 안쪽 경계 반지름인 $R_i$가 감소해야만 한다.

연직주입구로 부터 유입된 산화제 와류실 내부 유동의 일부분이 백홀쪽으로 진행하여 백홀의 뒤쪽 벽에 부딪혀 반사된다. 이 반사된 유동이 주 유동의 흐름을 방해하는 방향으로 발생하여 유량계수가 감소할 수도 있다. 그러나 그러한 경우에라도 유동면적이 유량계수의 감소보다 크게 증가하여 $\mu\pi(R^2 - R_i^2)$ 가 증가하여야 단위시간당 유량의 증가가 설명 가능하다. 이 때, 수정유량계수, $C_{dm}$을 정의하면

$$C_{dm} = \mu\pi(R^2 - R_i^2) \qquad (2)$$

백홀의 부피가 증가함에 따라 $C_{dm}$이 증가하여 단위시간당 유량이 증가한다고 볼 수 있다.

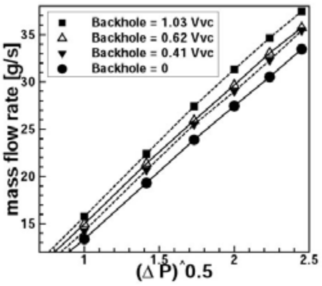


Fig. 4 Mass Flow Rate

## 6. 백홀 내부 유동

Fig. 5는 백홀쪽으로 짧은 시간 안에 발달하는 초기 유동을 시간 순서에 따라 나타내고 있다. 압력강하가 적용된 직후에는 Air Core 영역이 크게 형성되어 있지만 시간이 지나서 완전히 발달한 정상상태 유동이 되었을 때에는 Air Core 영역이 크게 줄어들고 계속 그 상태가 유지된다. 이러한 백홀 유동 특성 때문에, 단순히 길이가 긴 와류실을 가지는 경우와는 다른 분무 특성이 나타나게 된다.

Air Core의 반지름은 백홀이 존재하는 영역 전반에 걸쳐 거의 일정한 값을 가짐을 알 수 있다. 그리고 백홀의 크기가 증가할수록 Air Core의 길이가 증가하기 때문에 Air Core의 부피는 점차 증가한다.

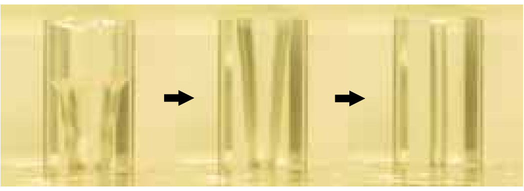


Fig. 5 The transient inner flow of the backhole

## 7. 음향 감쇄자로서의 백홀

음향계에서 Side Branch가 음향 Inertance와 Compliance를 가지고 있으면 그것은 Band-stop 필터로 작용하게 된다. Fig. 6과 같이 수렴하는 노즐 형상을 가지는 스월 인젝터의 경우를 가정하자. 이때, 스월 인젝터의 설계론에서 인젝터 내부의 액막 두께는 유동 면적 계수와 노즐 반지름의 함수로 다음과 같이 표현 가능하다.

$$h_L = \left(1-\sqrt{1-\phi}\right)R_n \tag{3}$$

또한 Air Core의 반지름이 백홀 전체에 걸쳐 거의 일정하다고 가정하면, 백홀의 Air Core 단면적과 부피는 각각 다음과 같다.

$$\begin{aligned} S_b &= \pi\left(\sqrt{1-\phi}\,R_n\right)^2 \\ V &= \pi(1-\phi)R_n^2\left(L_{VC}+L_B\right) \end{aligned} \tag{4}$$

그러므로 백홀이 있는 스월 인젝터의 전달계수(Transmission coefficient)를 0으로 하는 공진주파수의 기본모드는 다음의 식 (5)와 같다.

$$f_{B0} = \frac{a}{2\pi\sqrt{\left(L+1.7\sqrt{1-\phi}\,R_n\right)\left(L_{VC}+L_B\right)}} \tag{5}$$

식 (5)에서 백홀 스월 인젝터의 공진주파수는 유동의 액막 두께와 백홀의 길이에 따라 그 값이 변화한다.

Air Core가 인젝터 내부에 걸쳐서 일정한 반지름을 가지면서 분포한다는 가정 하에서는 백홀을 Quarter-wave resonator로 간주할 수도 있게 된다. 이 경우, 공진주파수의 기본모드는 다음과 표현되어 백홀의 길이에 주로 영향을 받는다.

$$f_{BQ0} = \frac{a}{4\left(L+0.85\sqrt{1-\phi}\,R_n+L_{VC}+L_B\right)} \tag{6}$$

이 때 백홀의 전체적인 형상은 그 길이를 제외하고 두 경우 모두 공진주파수에 큰 영향을 주지 않음을 알 수 있다. 또한 백홀이 증가함에 따라 스월 인젝터의 주파수 영역이 보다 낮은 주파수대로 옮겨가는 것을 알 수 있다.

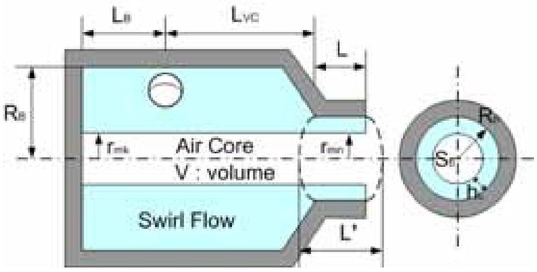


Fig. 6 The swirl injector as a Helmholtz resonator

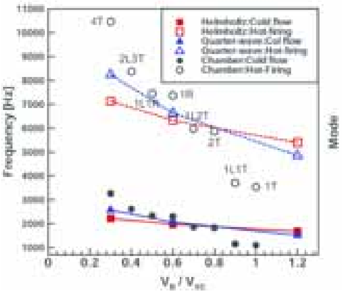


Fig. 7 Injectors and combustion chamber frequencies simulation of RD-0110 engine : Injectors have imaginary backholes

## 8. 백홀의 음향학적 필터로서의 역할

이상적인 원기둥형태의 연소실을 Closed /Closed system으로 가정하면, 공진주파수는 다음의 식 (7)과 같이 구할 수 있다.

$$f_{mn} = \frac{a}{2\pi}\sqrt{\frac{\lambda_{mn}^2}{R_C^2} + \frac{l^2\pi^2}{L_C^2}} \tag{7}$$

위의 식의 이론값은 실제값과 매우 유사하다고 알려져 있으며 비연소 실험의 주파수에 대략 3.2배를 하면 실제 로켓엔진의 연소 환경에서의 주파수가 된다고 알려져 있다.

백홀이 장착되었다고 가정한 RD-0110 엔진 스월 인젝터의 공진주파수를 연소실의 주파수와 비교하여 Fig. 7에 나타내었다. 스월 인젝터의 공진주파수와 연소실의 고유주파수들이 백홀의 조절에 따라 중첩될 가능성이 높음을 알 수 있다. 그러므로 특정 주파수에 조절된 백홀을 가지는 스월 인젝터를 인젝터면에 배치하면 연소불안정을 억제할 수 있는 효과를 얻을 수 있으리라 예상된다.

## 9. 결 론

백홀은 스월 인젝터의 새로운 기하학적인 설계요소로서 와류실의 연직주입구 후방에 위치하는 여분의 빈 공간을 총칭한다. 백홀은 유동의 중심부를 강화시켜서 단위시간당 유량을 증가시킨다. 또한 분무각은 백홀을 통하여 조절 가능하였다. 이러한 백홀의 분무각 조절은 스월 인젝터에서 산화제와 연료의 혼합 효율에 큰 영향을 주어서 스월 인젝터가 최적의 혼합 효율을 가지도록 할 수 있었다. 그러므로 액체 로켓 엔진의 스월 인젝터에서 백홀은 수력학적인 성능을 향상시킬 수 있는 조건을 만들어 줄 수 있다.

스월 인젝터의 백홀은 인젝터의 Air Core 영역이 Helmholtz resonator 또는 Quarter-wave resonator로 작용할 수 있도록 하는 기하학적 변수라고 할 수 있다. 이를 적용하기 위하여 음향학과 인젝터 설계 변수들을 사용하여, 실질적으로 특정 주파수에 맞출 수 있는 인젝터 설계식을 제시 하였다. 또한 연소실 내부의 고유주파수들과 인젝터의 고유주파수가 백홀의 조절을 통하여 중첩됨으로 연소불안정을 제어할 수 있는 가능성을 보여 주었다. 이것은 연소불안정이 가장 큰 문제점으로 부각되었던 KSR-III 엔진을 보완하고 나아가 향후 우리 나라 고유의 소형위성발사체가 될 KSLV의 엔진 개발에서 연소불안정을 조절하는 기본 자료로서 사용될 수 있을 것이다.

# Backhole as a New Geometric Parameter and Acoustic Damper for the Swirl Injector in the Liquid Rocket Engine

## I. Introduction

Swirl injectors are trustworthy on operating and have high efficiency of the atomization and the mixing compared with impinging type injectors widely used in western rocketry. In addition, the swirl injectors lead to more stable combustion compared with impinging types. So, Lots of rocket systems adopt the swirl injector system these days including KSLV ongoing rocket of the South Korea but the swirl injector has been mainly used on Russian rocketry by this time. However it is difficult to manufacture swirl injectors because of the complicated shape and configuration. And the analysis of the performance is not easy owing to the non-linear characteristics of them.[1, 2, 4]

On the liquid rocket engine spray system, the stable flow or injected spray is very important to the stable combustion and the efficiency of the combustor.[1~7] Because impertinent spray injection and induced oscillation can cause the fatal combustion instability, one of the real roots of the injector design process is the stabilizing of the oscillation. To make it possible that the effective suppression of the flow (mass flow, pressure, etc) oscillation or pulsation in the vortex chamber, new geometric design parameter is considered. Because it is well known that the geometric parameters are very important on the swirl injector and the feed line system, many of geometric parameters have been researched until now.[3] To design the swirl injector, Russian researchers contrived geometric non-dimensional parameters such as the geometric characteristics and the flow area coefficient that are considered to dominate over the performance of the swirl injectors.[1, 2, 4] However these efforts, there are only a few damping systems on the feed lines and combustion chamber such as cavities and baffles. And an effective device for the swirl injector has not invented.

So, the direct damping system of the swirl injector given its name “Backhole” was designed for the first time in this research. To suppress the pulsation of the vortex chamber flow and the fatal frequencies involved in the combustion instability, a new geometric design parameter (backhole) is contrived. Backhole is defined as an extra volume that is located behind the tangential entries at the rear part of the vortex chamber in the swirl injector.[8] The model injector schematics are presented in Fig. 1. Until now, most of the swirl injectors have no additional part, which is called as backhole, and the tangential entries are located at the end of the vortex chamber of the swirl injector. But if the swirl injector has the backhole, the vortex chamber flow could be changed and the flow characteristics of swirl injectors could be changed, too. Furthermore backhole is also a kind of resonator or filter in the swirl injector.[9] Backhole is an application of a vortex damper of high frequency pressure pulsation in the feed line system invented by V. G. Bazarov.[3] The centrifugal pressure pulsations waves influenced by previous circumferential velocity fluctuations: the memory effect of swirl flow. This effect allows containing these fluctuations in anti-phase so to suppress them.

According to the flow characteristics and this effect, cold-flow injector tests and theoretical acoustic analysis were performed. To find characteristics of the swirl injector with backholes, experiments are conducted by using a stroboscopic photograph, a PDPA apparatus and a mechanical patternator. And model injectors were made following the Russian design process. To examine the inner flow motion of the backhole, transparent material swirl injectors were also made.[1, 4]

## II. Experimental methods and apparatus

The spray cone angles were measured by the backlit stroboscopic photography. The stroboscopic lamp blinks with 60Hz frequency and a digital camera synchronized with the lamp took the flow images. All images were taken by the direct and the indirect photography. To confirm the test of significance, all images were taken repeatedly over 10 times at every experimental case.

To measure the mass distribution and the mixing efficiency, the mechanical patternator was used. The spray is collected in 180 cylinders through 180 lattice cells. The size of the lattice cell is 10mm×10mm and its lattice wall thickness is 1mm. Experimental data were obtained by the density difference between kerosene for fuel and water for oxidizer simulant. All data were measured at the 50mm and 70mm downstream points from the model swirl injector post. It is known that the liquid sheet or ligaments are disintegrated before they reach at these points. And it is also known that the flame forms within 50mm region of the liquid rocket engine combustor usually. The gathering of the injected flow was maintained during 35seconds. The mechanical patternator has the cover of the lattice cells controlled automatically. Then the flow of early 5 seconds was dropped so that the transient flow could be excluded.

Liquid droplet size, velocity of droplets and their size distribution were observed by using PDPA (Phase Doppler Particle Analyzer). A Spectra-Physics Ar-ion laser which wavelength is 514.5nm was taken to measure the droplet size, velocity and so on. To obtain the droplet size and the axial velocity of the droplets, SMD (Sauter Mean Diameter) was chosen and measured at the 50mm and 70mm downstream points from the model swirl injector posts similar with the case of the mechanical patternator experiments. Most of numbers of sample droplets were obtained over 10000 and the measurement was repeated 3 times at every measurement point. And the whole injected flow field was scanned at every 2mm by PDPA.

The descriptive schematic of the model swirl coaxial injector is shown in Fig. 2. The oxidizer nozzle has 4 tangential entries and every entry separates uniformly. Its nozzle diameter is 1.8mm and geometric characteristic is 1.08. And it has a typical convergent nozzle shape. On the other hand, the fuel nozzle has 3 tangential entries and every entry separates equally, too. Its nozzle diameter is 4.5mm and its nozzle shape is a convergent. Pins that have various lengths control the backhole volume and can be snapped in the oxidizer nozzle. The model swirl coaxial injector is able to have 16 kinds of recesses and 6 kinds of backholes. In this research, 6 kinds of recesses and 6 kinds of backholes are taken to make experiments. To find the characteristics of the inner side flow of backholes, additional model swirl injector with transparent material was made. This transparent injector has 4 tangential entries and 3 kinds of backholes.

In order to analyze theoretically, the nomenclature of this research is presented in Table. 1. The summary of experimental conditions of geometric parameters is presented in Table. 2. And operating conditions of the model swirl injectors are shown in Table. 3.

**Table. 1 Nomenclature**

| | | | |
|---|---|---|---|
| A | Geometric characteristics | n | Nozzle or radial mode |
| $a$ | Sound speed | ox | Oxidizer |
| B | Backhole | $\Delta$P | Pressure drop |
| C | Combustion chamber | Q | Quarter-wave resonator |
| $C_{dm}$ | Modified discharge coefficient | R | Radius |
| D | Diameter | r | Flow radius |
| F | Fuel or frequency | Re | Recess |
| H | Helmholtz resonator | S | Area |
| h | Thickness | V | Volume |
| i | Inner | VC | Vortex chamber |
| L | Length or liquid | 0 | Fundamental mode |
| L’ | Effective length | $\varphi$ | Flow area coefficient |
| l | Longitudinal mode | $\lambda$ | Eigen value of Bessel function |
| m | Tangential mode | $\rho$ | Density |
| $\dot{m}$ | Mass flow rate | $\mu$ | Discharge coefficient |

**Table. 2 Experimental conditions of geometric parameters**

| Parameter | Experimental conditions |
|---|---|
| $L_{\mathrm{Re}} / d_{ox}$ | 0, 1.39, 1.53, 1.67, 1.81, 1.95 |
| $V_B / V_{VC}$ | 0, 0.21, 0.33, 0.52, 0.62, 0.67, 0.83, 1.03, 1.22 |

Table. 3 Operating conditions of the model swirl injectors

| | | Oxidizer | Fuel |
|---|---|---|---|
| Simulant | | Water | Kerosene |
| Co-flow conditions | Pressure drop | 0.3MPa | 0.4MPa |
| | Mass flow rate | 23.9g/s (varies with backholes) | 10.8g/s |
| Pressure drop | | 0.1MPa ~ 0.6MPa (varies) | 0.4MPa |

## III. Backhole flow characteristics

### a. The spray cone angle and the mixing efficiency

Spray cone angle is the main parameter that decides the distribution of liquid drops and the mixing efficiency of propellants. Up to the present results, the recess and the pressure drop dominate the spray cone angle of swirl injectors mainly. However the spray cone angle is also varied by various backholes. With recesses, backhole controls the spray con angle of swirl injectors about 28% at its maximum.

Fig. 3 shows the spray cone angle of the swirl coaxial injectors with the shallow recesses. When the swirl injector has shallow recesses or non-recess, the spray cone angle of the inner side injector (usually oxidizer injector) of the swirl coaxial injector is decreased as the backhole is increased. The decrease of the oxidizer spray cone angle can lead not to collide the oxidizer flow against the fuel flow under the mixing criteria. In case of the outer mixing injection, the decreased spray cone angle is not preferable.

But when the swirl injector has deep recesses, the spray cone angle of the swirl coaxial injectors is varied in different ways. Fig. 4 presents the spray cone angle of the swirl coaxial injectors with the deep recesses. If the inner nozzle had the large backhole volume, the spray cone angle of the swirl coaxial injector would be enlarged compared with that of the non-backhole injector. On condition that the backhole volume is not enough, the spray cone angle of the inner nozzle is not decreased sufficiently. Then the inner nozzle flow can be interfered with the outer nozzle wall. So, the inner flow losses some amount of its momentum and the spray cone angle is decreased drastically. If the inner nozzle had the large enough backhole volume, the spray cone angle would be decreased pertinently so that the inner flow is not interfered with the outer nozzle wall. Therefore the spray cone angle is enlarged compared with that of the non-backhole injector. But, on condition that too excessive recess exists, the spray cone angle is not varied by the backhole largely.

Even if the spray cone angle was decreased by the backhole, that of the swirl coaxial injectors would be not changed largely. Because of the momentum of the outer injected flow (usually fuel flow), the overall spray cone angle maintains averaged values. Therefore there is little difference of the spray cone angles between the backhole swirl coaxial injector and the non-backhole swirl coaxial injector. So, the backhole does not narrow the distribution of the injected flow generally.[8] In Fig. 5, there is a little total area difference between the case of $V_B/V_{VC}=1.03$ and that of $V_B/V_{VC}=0$. But the mixing efficiencies of the two cases are not same.

The backhole controls the spray cone angle more finely compared with recess. Well-tuned spray cone angle contributes to the better mixing condition and better combustion condition usually. These spray con angle variation can cause the mixing efficiency variation of the swirl coaxial injectors. If the swirl coaxial injector had only the recess, the mixing efficiencies due to recesses would be shown the tendency like Fig. 6. Mixing efficiencies can be earned from the Rupe’ s mixing factor equation.[10] It is the widely used equation to examine the degree of locally well-distributed propellants compared with an intended value.

Usually as the recess is increased, the mixing efficiency is also increased to some degrees. When the inner flow collides with the outer nozzle post, it is known that the mixing efficiency reaches at its maximum value.[4, 11] And the emulsion injection is better than the outer mixing injection. However the mixing efficiency variation due to recesses is changed extremely. Even if the recess was modified a little millimeters (1~2mm), the mixing efficiency could be varied about 30%. So, it is not easy thing to gain the maximum mixing efficiency from modifying recesses only.

To be different, backholes change the mixing efficiency of the swirl coaxial injectors more gradually. Nevertheless the swirl injector has a fixed recess; the mixing efficiency is varied along the variation of backholes. Fig. 7 shows that backholes change the mixing efficiency of the swirl injector with the fixed recess over the 20%. Because backholes decrease the spray cone angles gradually, it is possible that well designed backhole makes the inner flow meeting with the outer nozzle post. Therefore the mixing efficiency can reach at its maximum in spite of the fixed recess condition. However the backhole exists, too much excessive backhole volume can cause the mixing efficiency drop. So, there is an optimum value of the backhole volume (about 60%). Consequently, with the backhole, combined with the recess, the fine-tuning spray cone angle can be earned so that the optimal mixing condition can be earned.

### b. The increase of the inner flow motion and the mass flow rate

In spite of maintaining the pressure drop of the swirl injector constantly, the mass flow rate was increased gradually along the increase of the backhole. Fig. 8 presents the tendency to increase of the mass flow rate about 15%. Generally in case of the swirl flow injection; the flow section area forms a ring shape. Considering the ring section, the mass flow rate is expressed by the following equation (1).

$$\dot{m} = \mu\left(R_{ox}^2 - r_i^2\right)\sqrt{2\rho\Delta P} \qquad (1)$$

In the equation (1), $R_{ox}$, and $\rho$ are fixed values at experimental conditions individually. And the mass flow rate is also increased despite $\Delta P$ is also fixed individually. To be increased the mass flow rate, $\mu$ must be increased or $r_i$ must be decreased. If $\mu$ is decreased owing to the increase of the backhole, $r_i$ should be decreased enough to compensate for the decrease of $\mu$. Although $\mu$ is increased by backholes, the injected flow shows the decrease of the $r_i$. To confirm the decreased $r_i$, the injected flow was captured by using a mechanical patternator. Fig. 9 shows the patternation of the oxidizer flow with various backholes. As the backhole volume increased, $r_i$ is decreased about 83%. These drastic decrease lead to increase the flow section area so that the mass flow rate can be increased.

It is also found that the flow section inside the vortex chamber or backhole is increased along the increase of backholes. The visualization of the inside backhole region (Fig. 10 (a)) presents the inner flow radius is decreased as the backhole volume is increased similar to the case of the injected flow capture. The left side picture is the case of $V_B / V_{VC} = 0.67$ and the right side is the case of $V_B / V_{VC} = 1.22$. Because the decrease of $r_i$ is not so large at the inside of the backhole, the increase of the backhole length is to increase the air core volume to some degrees (Fig. 10 (b)). Usually total volume of the injector is not large enough and the increase of the air core diameter is a bit slight (about 8%~15%). If the backhole length were increased too much, the air core volume would be decreased due to the increase of the flow section area. In our model injector case, the air core volume reaches at its maximum value near the condition of $V_B / V_{VC} = 1.00$.

Considering the increase of $\mu$ and the decrease of $r_i$, the overall discharge coefficient could be defined as the following expression.

$$C_d = \mu\left(R_{ox}^2 - r_i^2\right) \tag{2}$$

So, it is concluded that backholes make the overall discharge coefficient $C_d$ enlarged. Backholes reinforce the center region of the swirl and the injected flow. The flow transition could occur in the injected swirl flow transformed from the hollow cone shape to the solid-like cone shape. Although this transition occurs the shape of the injected flow remains the hollow cone shape. This phenomenon relates to the inside flow motion of backholes.

The free surface shape of the air core remains nearly cylindrical for low inlet velocity, whereas the shape of the air core is found to be helical at steady state for higher inlet velocity.[12] No matter what the backhole volume is, the shape of the air core is almost an ideal cylinder (Fig. 10 (a)). But at transient state, turbulent wakes and eddies are developed on the surface of the air core. But these turbulent phenomena fade out in a short time and the flow becomes the fully developed state soon (Fig. 11)

The transient inside flow motion of the backhole region is presented in Fig. 11. When the pressure drop is given to the swirl injector, the swirl flow is developed toward the both front and the rear part of the tangential entries simultaneously. The backward flow is developed until it touches the end wall of the backhole. When that flow reaches the wall, it is reflected onto the wall and the reflected flow goes forward to the nozzle exit again. During this flow reflection the air core volume is decreased quickly. When the whole flow motion becomes the fully developed state, the air core radius keeps a certain value as long as the pressure drop remains. And this transient flow development occurs at any position of the swirl injector.

Without the backhole, when the vortex chamber is long enough to compensate for the length of the backhole simply, the frictional loss might become an issue. According to Bazarov's criterion, the following relation (3) can express the frictional loss of the vortex chamber.[4]

$$\frac{\left(R_n / r_{in}\right)^2}{n} - A \leq 6.5 \tag{3}$$

Where $r_{in}$ is the tangential entry radius, $n$ is the number of tangential entries and $A$ is the geometric characteristics of the swirl injector. The left side is less than one so inequality (3) is valid.

(The geometric characteristics of the model swirl injectors are about one for the oxidizer nozzle) And the total length of the injector is not so long. Generally its length is about 1.5cm~3.5cm. So if the inequality (3) is not valid on this case, the losses caused from the extended flow path could be not large because of its short total length generally. Then the frictional loss is ignorable in the model swirl injectors. Therefore the main cause of the unique characteristics of these phenomena are not the frictional loss of the backhole but the inside backhole flow motion.

### c. Atomization efficiency

The increase of backhole volume leads to the increase of the liquid film thickness. And the increase of backhole also leads to the increase of the mass flow rate of the swirl injector at same pressure drop condition. This effect can cause ill atomization.[2, 13, 14] However these phenomena occur, it is hard to say that the backhole causes the ill atomization efficiency statistically. Using PDPA, SMD was measured every 2 millimeters on the spray field. In spite of increased mass flow rate, SMD of the swirl injectors would not be increased greatly. Fig. 12 shows the SMD of the backhole swirl injectors. In case of the backhole with 103% vortex chamber volume ($V_B / V_{VC} = 1.03$), the SMD of the swirl injector is increased about 10% compared with that of the non-backhole injector case so overall atomization efficiency is decreased. But in case of the backhole with 21% vortex chamber volume ($V_B / V_{VC} = 0.21$), the most efficient atomization is earned of all over the cases on the average. And in case of the backhole with 52% vortex chamber volume ($V_B / V_{VC} = 0.52$), the SMD of the swirl injector is almost the same as that of non-backhole swirl injector. Even if the SMD of the swirl injector is increased, atomization efficiency can be compensated by slight increase in pressure drop.[6]

Generally speaking, backhole does not decrease the axial velocity of the swirl flow. Even though it decreases the axial velocity of the swirl flow, the decrease of the velocity is not enough to decrease the atomization efficiency. If the backhole decreases the axial velocity drastically, the increase of the mass flow rate cannot be explained. Fig. 13 presents the axial velocity of the swirl flow over the backhole volumes. The decrease of the axial velocity due to backhole does not exceed 5% of non-backhole injector case. Then the almost constant axial velocity induces the almost constant Reynolds number flow and Weber numbers of most of cases are almost constant. That is why the backhole does not harm to the atomization efficiency. Even if the backhole is increased to about 100% vortex chamber volume, the atomization efficiency does not decrease greatly.

## IV. Backhole as an acoustic band-stop filter

### a. Theoretical analysis

On an acoustic system, when the side branch has the acoustic inertance and the compliance, the side branch can function as a band-stop filter.[15, 16] It is possible that the swirl injector is regarded as a Helmholtz resonator in case of the convergent nozzle shape. If the air core radius is almost constant along the backhole, it can be regarded as a quarter-wave resonator, too. If a swirl injector was considered as a Helmholtz resonator or a quarter-wave resonator, the air core could work as an acoustic resonator. Then, the natural frequency of the Helmholtz resonator is

$$f = \frac{a}{2\pi}\sqrt{\frac{S}{VL'}} \tag{4}$$

Following the swirl injector design process, the liquid thickness $h_L$ is defined as the function of the flow area coefficient $\varphi$ and the nozzle radius $R_n$.[4] The backhole swirl injector schematic is presented at Fig. 14.

$$\varphi = 1 - r_n^2 / R_n^2 \tag{5}$$

$$h_L = \sqrt{1-\varphi}R_n \tag{6}$$

For a constant air core radius

$$S = \pi(R_n - h_L)^2 = \pi(1-\varphi)R_n^2 \tag{7}$$

$$V = \pi(1-\varphi)R_n^2(L_{VC} + L_B) \tag{8}$$

At the entrance of the injector, the gas is expanding and compressing alternatively. So, the effective length $L'$ is needed. By the piston oscillation, the load of surrounding media is equal to the mass of fluid contained in the cylinder of its length $8R_p / 3\pi$.[15] ($R_p$ is the radius of the piston) If the mass load of both ends of a Helmholtz resonator entrance is the same as the mass load of the piston, the effective length becomes

$$L' = L + 2\Delta L = L + \frac{16R_p}{3\pi} = L + \frac{16\sqrt{1-\varphi}R_n}{3\pi} = L + 1.7\sqrt{1-\varphi}R_n \tag{9}$$

Therefore the fundamental mode of backhole swirl injectors becomes

$$f_{BH0} = \frac{a}{2\pi}\sqrt{\frac{S}{L'V}} = \frac{a}{2\pi\sqrt{L'\left(L_{VC}+L_B\right)}} = \frac{a}{2\pi\sqrt{\left(L+1.7\sqrt{1-\varphi}R_n\right)\left(L_{VC}+L_B\right)}} \tag{10}$$

According to the equation (10), due to the sound speed, the liquid film thickness, the length of vortex chamber and the backhole length, the resonance frequency of the backhole swirl injector can be changed. In case of the excessive backhole length, the liquid film thickness is increased largely. Then the inner swirl flow of the vortex chamber is not well developed and the atomization efficiency can fall. So, the relationship between the backhole length and the air core volume must be considered. But the value of $1.7\sqrt{1-\varphi}R_n$ is usually much smaller than that of $L$, it is possible that the backhole length is the only geometric parameter that can tune the resonance frequency uniquely.

On the assumption that the air core is distributed along the inside of the injector with a constant radius, it is possible that the backhole can be considered as a quarter-wave resonator, too. Such kind of cases, the fundamental resonant frequency mode of the backhole swirl injector is equal to the equation (11). Nearly the same as those of the Helmholtz resonator case, the variable parameters of the equation (11) are the sound speed, the length of the vortex chamber, the liquid film thickness and the backhole length.

$$f_{BQ0} = \frac{a}{4\left(L'+L_{VC}+L_B\right)} = \frac{a}{4\left(L+0.85\sqrt{1-\varphi}R_n+L_{VC}+L_B\right)} \tag{11}$$

According to the equation (10) and (11), the shape of the backhole without its length does not affect the resonance frequency of the backhole swirl injector. But the backhole shape could affect the flow characteristics of the backhole swirl injector. And as the backhole length is increased, the backhole swirl injector has the lower resonance frequency. These phenomena resemble the effects of wind instruments. This only increase of the resonator (backhole) length can tune the resonance frequencies of resonators easily.

### b. Application to RD-0110 engine

To confirm above results, the backhole was adapted to the 3rd stage engine of Russian Soyuz, RD-0110 simulation. It is assumed that the combustion chamber of RD-0110 is an ideal cylindrical shape that radius $R_C$ is 90mm and length $L_C$ is 500mm. (Fig. 15[11]) And both sides of the combustion chamber are closed acoustically. Then the longitudinal and the transverse modes of the combustion chamber can be earned by the equation (12).

$$f_{lmn} = \frac{a}{2\pi}\sqrt{\frac{\lambda_{mn}^2}{R_C^2} + \frac{l^2\pi^2}{L_C^2}} \tag{12}$$

It is well known that the values of equation (12) are the almost same as the experimental values.[17~20] The swirl injector schematic of RD-0110 is presented in Fig. 16.[11] And it is assumed that it has several imaginary backholes. The resonance frequencies of the swirl injectors with imaginary backholes can be earned using the equation (10) and (11). Under the hot-firing test, the sound speed is increased and the swirl injector is expanded by heat. So, like the equation (13), it is known that frequencies of the real hot-firing rocket engine condition can be earned by 3.2 times of the frequencies of the cold-flow acoustic test.[20]

$$\frac{f_{Hot}}{f_{Cold}} = \frac{a_{Hot}\left(L' + L_{VC} + L_B\right)_{Cold}}{a_{Cold}\left(L' + L_{VC} + L_B\right)_{Hot}} \cong 3.2 \tag{13}$$

Fig. 17 shows the resonance frequencies of the combustion chamber and backhole swirl injectors. The frequencies of the backhole swirl injectors and the combustion chamber are located at the similar band. So, it is within the range of possibility of piling the natural frequencies of the combustion chamber up on those of the backhole swirl injectors. In case of the backhole with 33% vortex chamber volume ($V_B / V_{VC} = 0.33$), the frequencies of backhole swirl injectors are similar with the high modes of the combustion chamber frequencies such as the 4th tangential mode. And in case of the backhole with 122% vortex chamber volume ($V_B / V_{VC} = 1.22$), those frequencies are similar with the fundamental mode of the combustion chamber frequency. That is to say, as the backhole increases, the resonance frequencies of the backhole swirl injectors are led in lower combustion chamber frequencies region. The frequency of the swirl injector with the backhole is decreased about maximum 34% compared with that of the non-backhole case. Consequently, if the backhole swirl injectors with fine-tuning with the combustion chamber frequencies were set at the injector plate, they would play a same role of the acoustic cavities in the combustion chamber. The combustion chamber frequencies will be suppressed by the superposition of the anti-phase frequencies of the backhole swirl injectors.

The tangential modes of the combustion chamber frequencies reach their maximum at the outer region of the combustion chamber and the radial modes reach their maximum at the center of the combustion chamber.[20, 21] And acoustic cavities should be set on the injector plate region as near as possible.[17~20] So, The possibility is high that the backhole swirl injectors could play a role of damping and filtering.

## V. Conclusion

Backhole is a new geometric parameter that influences the spray characteristics of the swirl injector. With backholes, it is possible to control the spray angle of the swirl injector about 28%. Owing to controlling of the spray cone angles, the optimum mixing condition could be earned combined with suitable recesses. And the ring section area is increased as the backhole is increased. So, the mass flow rate is increased about 15% compared with the case without the backhole. But the increase of the ring section area and the mass flow rate, it is hard to say the atomization efficiency is decreased greatly by Backholes. Consequently, based on cold-flow tests, these hydraulic characteristics of the backhole may improve the performance of the swirl injectors in the liquid rocket engine.

Backhole is a new acoustic damper that influences the frequencies of the swirl injector and the combustion chamber. Backholes play an important role regarding the swirl injector as a Helmholtz or Quarter-wave resonator. The frequency of the swirl injector with the backhole is decreased about 34% compared with the case without the backhole. The increase of the backhole length leads to replacement of injector-coupled instability regions in lower frequency range. So it is possible that there is the effective resonance between the frequency of the combustion chamber and the frequency of the swirl injector. Consequently, it is possible that the injection-coupled instability can be suppressed by the well-tuned backhole.

For the future works, backholes need to confirm the suppression ability of the combustion chamber frequencies considered to being involved the combustion instability under real hot-firing conditions. The hot-firing tests of the backhole as an acoustic damper will enable to develop the liquid rocket engine of KSLV without the combustion instability. Backholes can be good alternations of acoustic cavities.

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## VII. Figures

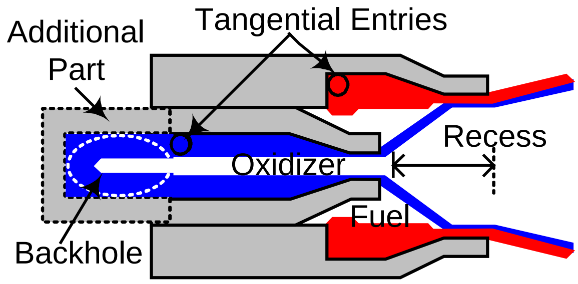
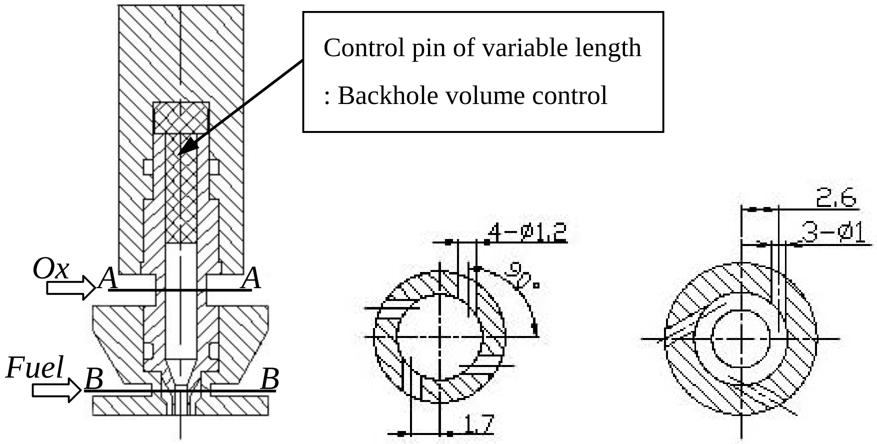
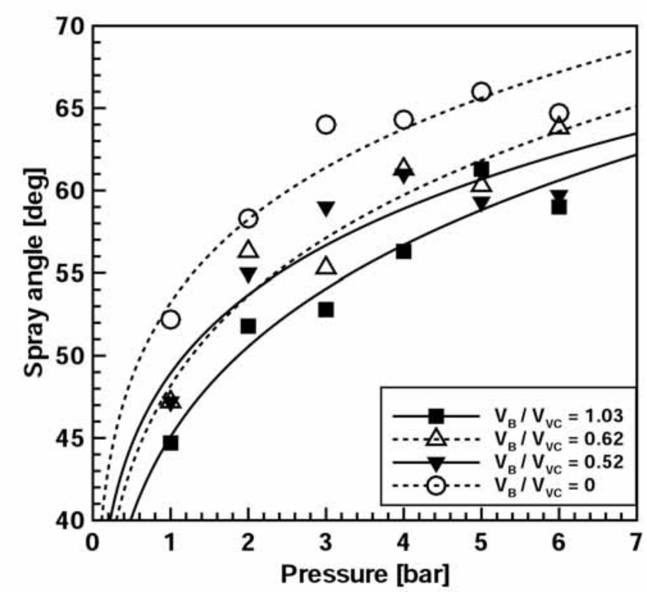


Fig. 1 Schematic of the backhole swirl injector

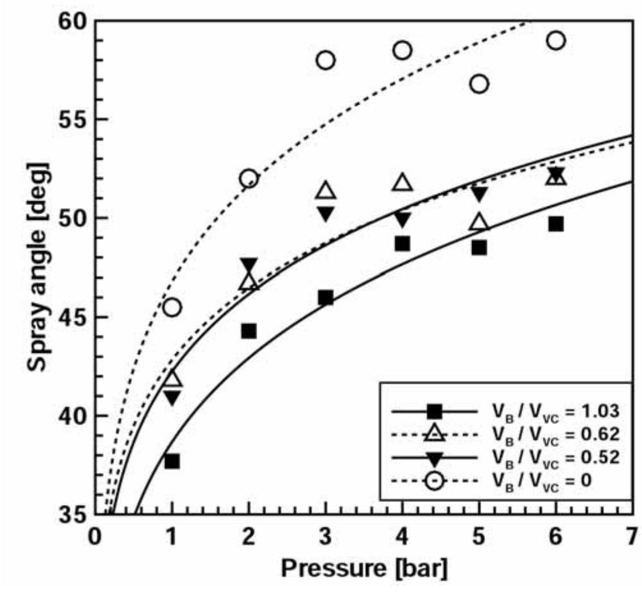


(a) Assembly (b) Section A-A (c) Section B-B

Fig. 2 Model swirl coaxial injector assembly

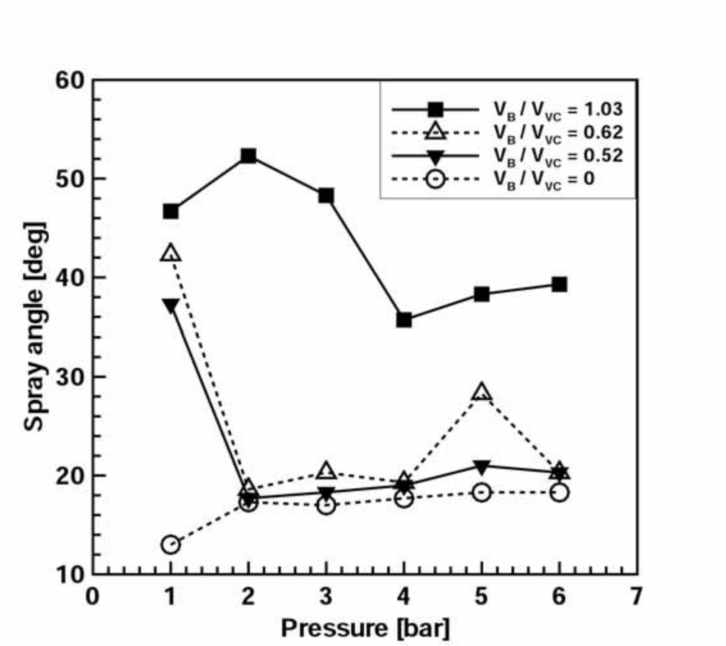


(a) $L_{\mathrm{Re}} / d_{ox} = 0$

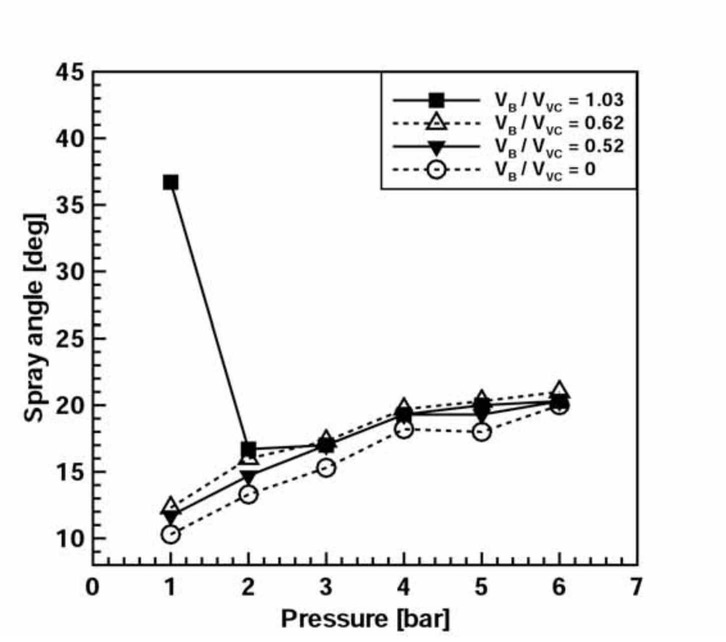


(b) $L_{\mathrm{Re}} / d_{ox} = 1.39$

Fig. 3 Spray cone angle variations of various pressure drops and shallow recesses

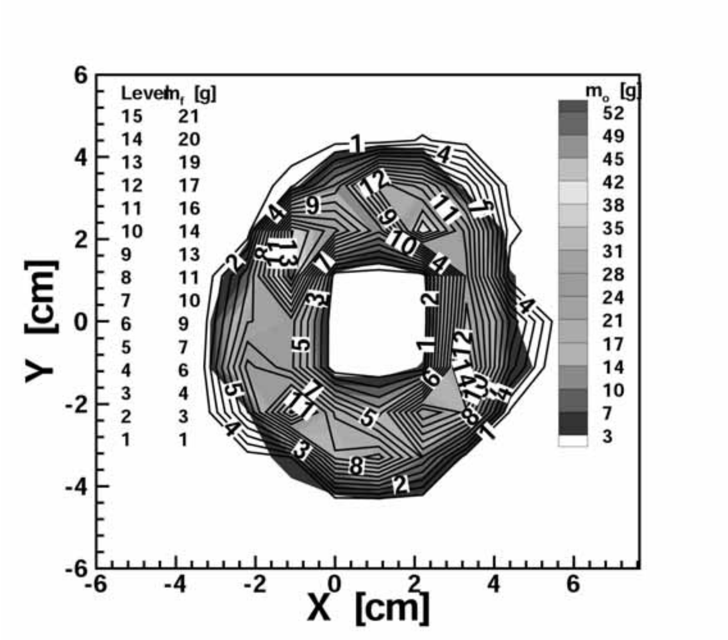


(a) $L_{\mathrm{Re}} / d_{ox} = 1.67$

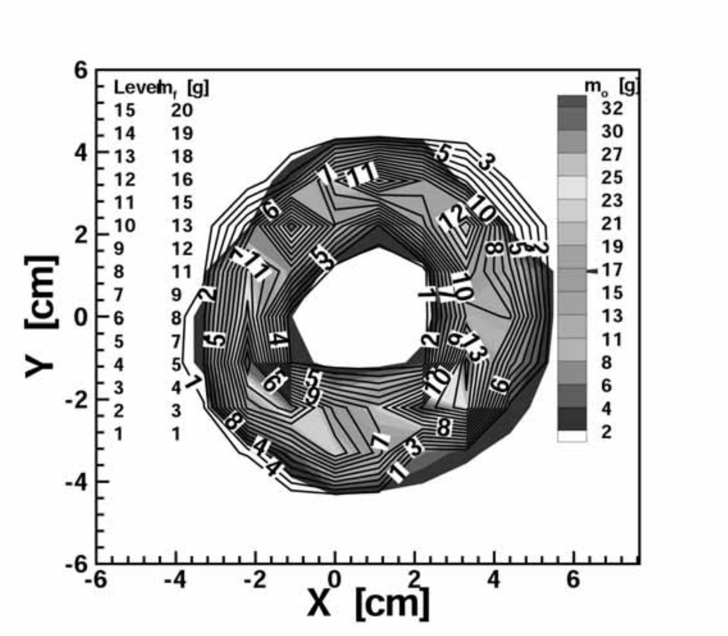


(b) $L_{\mathrm{Re}} / d_{ox} = 1.81$

Fig. 4 Spray cone angle variations of various pressure drops and deep recesses



(a) $V_B / V_{VC} = 1.03$



(b) $V_B / V_{VC} = 0$

Fig. 5 Patternation of the backhole swirl injectors at Z=70mm $L_{\mathrm{Re}} / d_{ox} = 1.67$

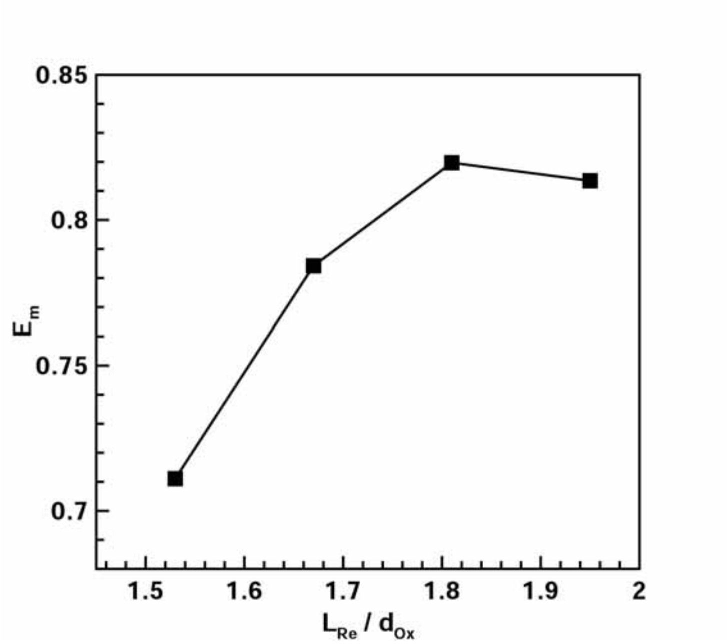


Fig. 6 Mixing efficiency with various recesses

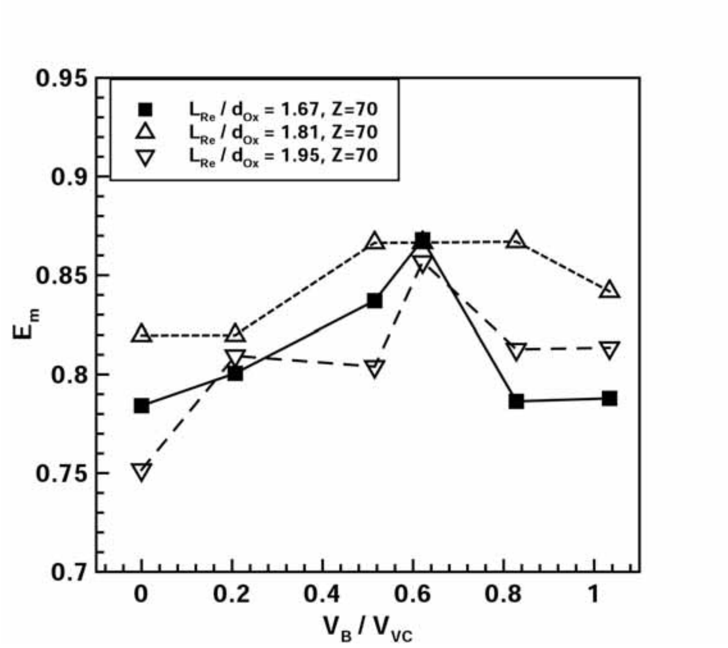


Fig. 7 Mixing efficiency with various recesses and backholes

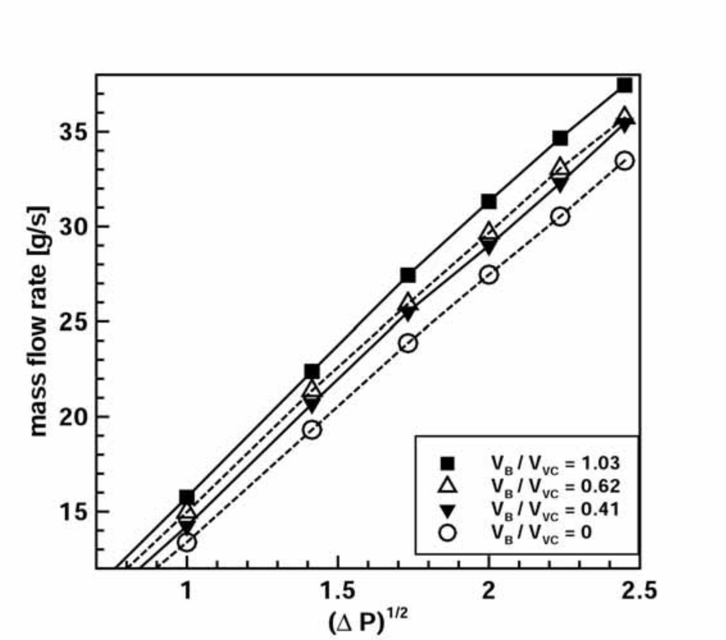
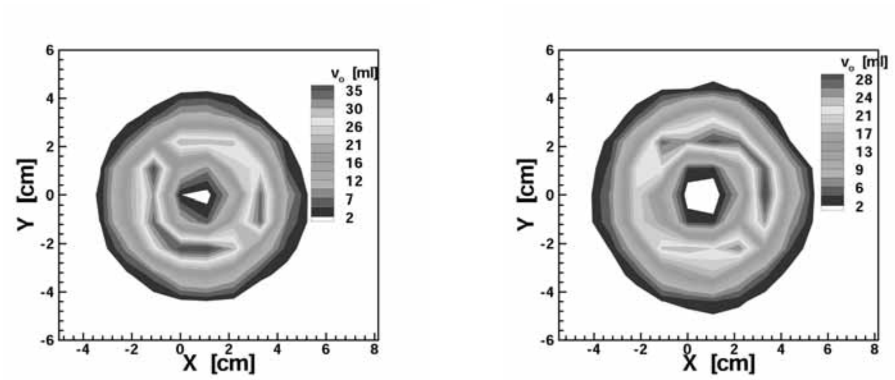
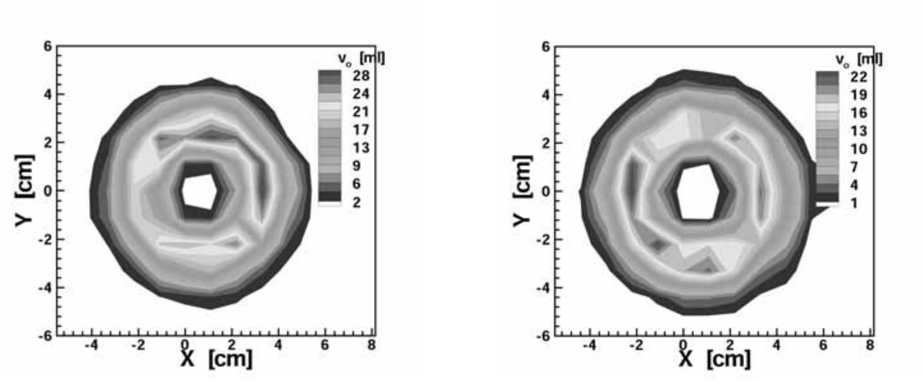


Fig. 8 Mass flow rate with various backholes



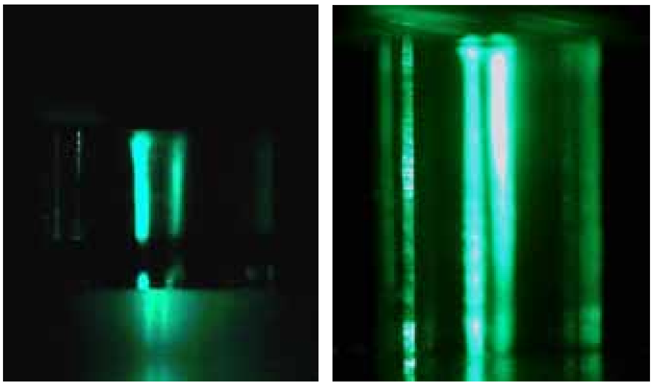
(a) $V_B / V_{VC} = 1.03$ (b) $V_B / V_{VC} = 0.62$



(c) $V_B / V_{VC} = 0.52$

(d) $V_B / V_{VC} = 0$

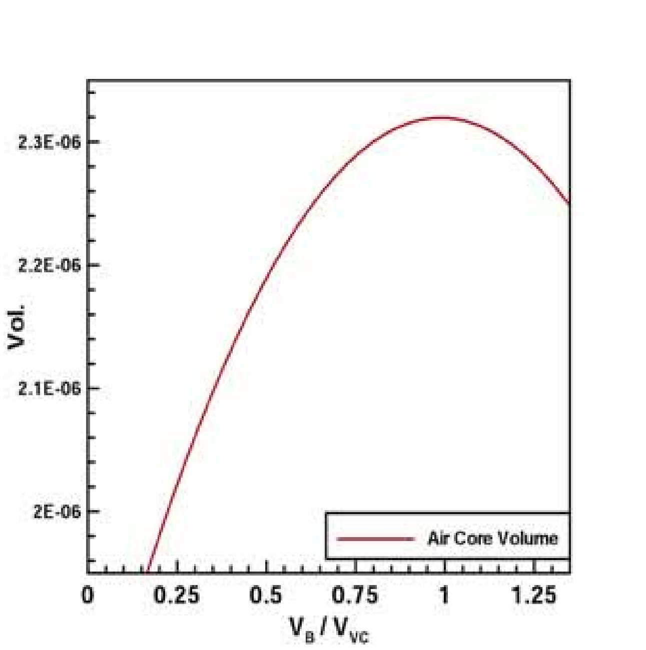
Fig. 9 Patternation of oxidizer with various backholes at Z=70mm, $L_{\mathrm{Re}} / d_{ox} = 0$



$V_B / V_{VC} = 0.60$

$V_B / V_{VC} = 1.20$

(a) The decrease of the inner flow radius with backholes



(b) The air core volume variation with bacholes

Fig. 10 The results of the visualization of the inside backhole region

Fig. 11 The transient inner flow of the backhole region

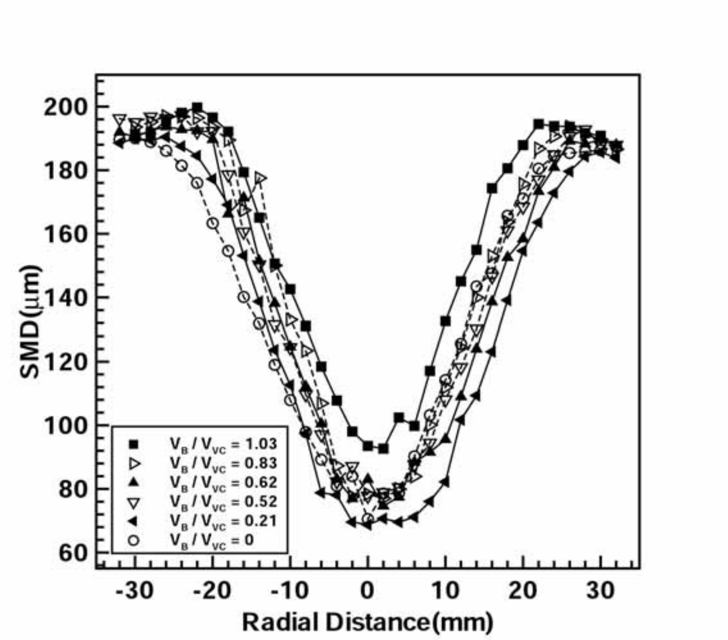


Fig. 12 SMD with various backholes (PDPA)

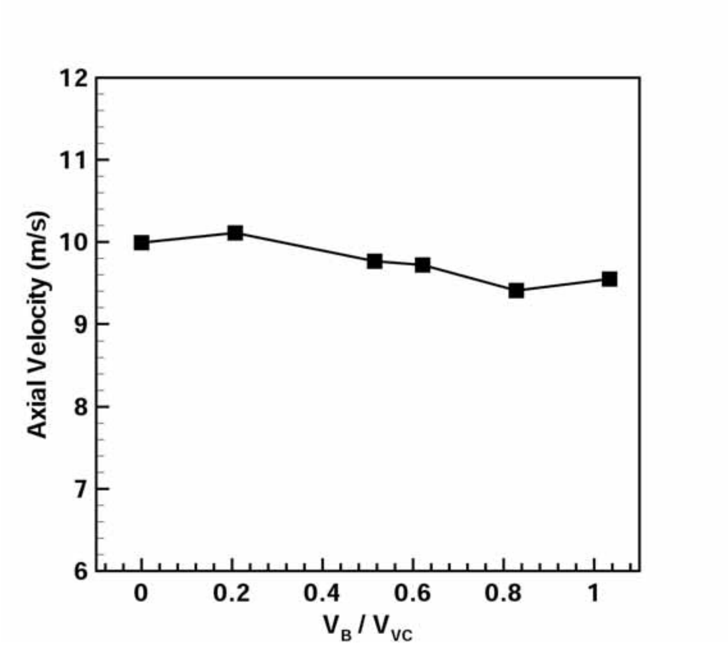


Fig. 13 Axial velocity of backhole swirl injectors

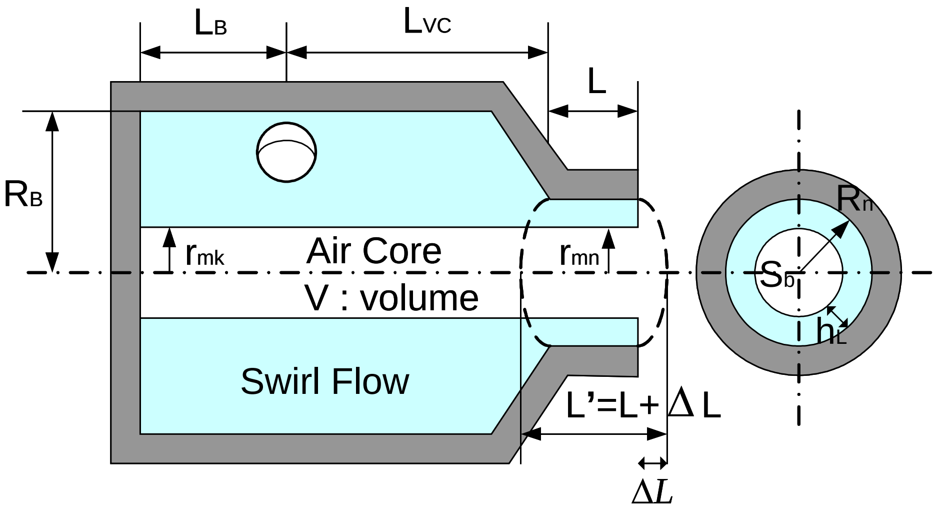


Fig. 14 The backhole swirl injector as a Helmholtz or Quarter-wave resonator

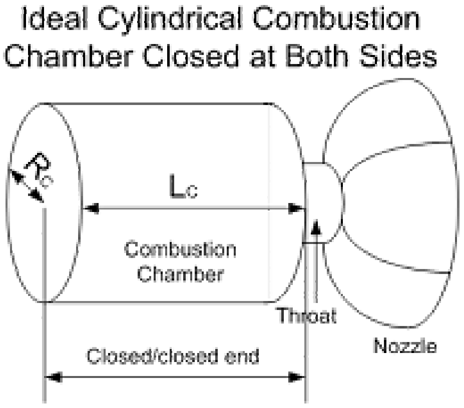


Fig. 15 Ideal cylindrical combustion chamber modeling

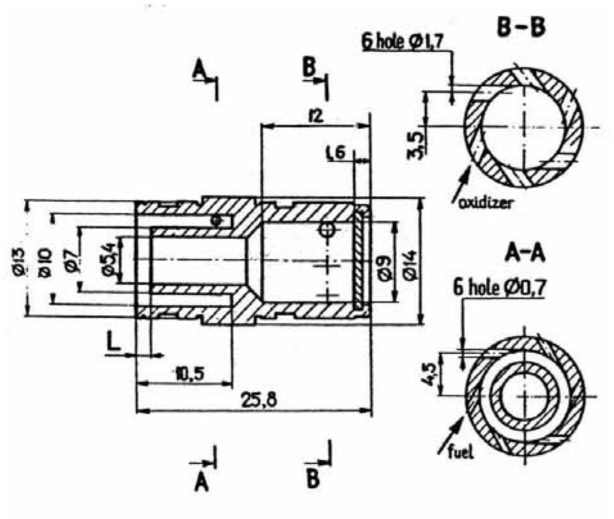


Fig. 16 The injector schematics of RD-0110 engine

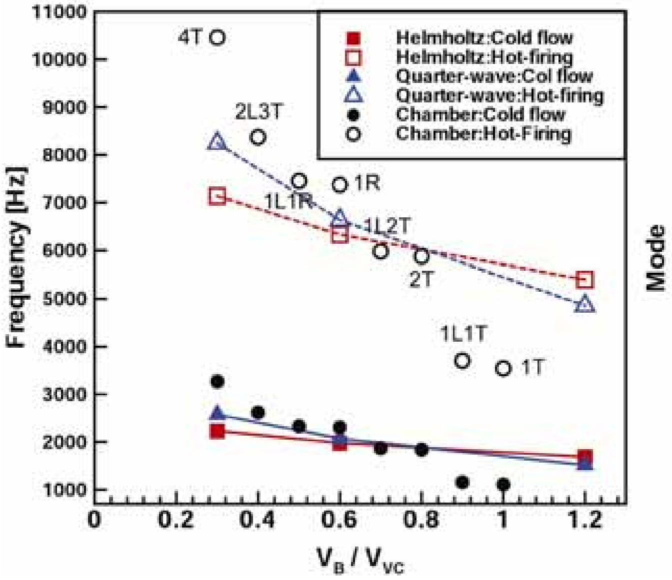


Fig. 17 Injectors and combustion chamber frequencies simulation of RD-0110 engine
: Injectors have imaginary backholes