Droplet Size Control in Gas-Liquid Pintle Injectors*

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Due to their suitable characteristics for throttleable rocket engines, interest in pintle injectors has been recently renewed. Many studies have focused on the correlation between spraying conditions and spray or combustion characteristics for pintle injector. However, there is no previous study on the correlation between spray and combustion characteristics due to the difficulties in controlling each spray characteristic individually. This research presents a solution to this problem. For the control group, a 400 N gas-liquid pintle injector for liquid oxygen and gas methane is designed and its spray characteristics are measured through cold-flow tests. In sequence, a ‘reverse injection’ idea and its design are proposed to increase spray angle while maintaining the droplet size, which is represented by the Sauter mean diameter. In addition, in the design proposed, the reverse injection effect is intensified as the throttling level increases, decreasing the difference of spray angle between throttling levels. In a cold-flow test, air and water were used under an atmospheric condition for gas-liquid flow simulant. The spray angle and droplet size were measured using the shadow method. The ‘reverse injection’ feature proposed functioned properly, increasing the spray angle of the injector while maintaining the droplet size.

Key Words: Gas-Liquid Pintle Injector, Droplet Size Control, Reverse Injection

Nomenclature

A : droplet candidate area, mm²
 c^* : characteristic velocity
 C_F : thrust coefficient
 D : droplet diameter, μm
 D_{pp} : pintle post diameter, mm
 D_{pt} : pintle tip diameter, mm
 $D_{pt,rod}$: pintle tip rod diameter, mm
 d : advance distance, mm
 d^* : end distance, mm
 G : annular orifice gap, mm
 h : pintle orifice height, mm
 K : normalized standard deviation
 M : droplet image judging constant
 $\dot{m}$: mass flow rate, g/s
 P : droplet candidate perimeter, mm
 r : reverse injection slot radius, mm
 u : velocity, m/s
 α : spray angle, deg
 θ : reverse injection angle, rad
 ρ : density, kg/m³
 σ : surface tension, mN/m

Subscripts

axi: axial flow
cold: cold-flow test condition
n: normal pintle tip
r: reverse pintle tip

rad: radial flow

real: real injection condition

1. Introduction

The pintle injector is an axisymmetric bipropellant impinging injector, in which one propellant is injected axially and the other radially, colliding nearly perpendicularly. In the pintle injector, it is possible to adjust the injection area of both propellant simultaneously as the mass flow rate changes, thus preserving the injection velocity while throttling. Since maintaining a certain amount of injection velocity is critical, the pintle injector is suitable for the throttling engine. The idea of using a pintle injector in liquid rocket engines was first proposed by JPL engineers in the mid-1950s. It is now being reexamined because of its excellent throttling ability, which is critical for reusable vertical-landing launch vehicles, such as the Falcon 9 equipped with Merlin series engines. The pintle injector is also known for its inherent combustion stability, scalability, and low cost.¹⁾

Despite the numerous advantages, the pintle injector is difficult to design and study academically due to its various design parameters and area changing mechanisms. Although limited, several research groups have investigated the spray characteristics of pintle injectors using the cold-flow test. Son et al. designed and studied the correlation between spraying conditions and spray characteristics of gas-liquid pintle injectors for years.^{2,3)} The authors targeted the two most universal spray characteristics in the injector field—spray angle and Sauter mean diameter (SMD). For spraying conditions, various parameters were applied, such as non-dimensional parameters (e.g., total momentum ratio (TMR) and Weber number (We)) between two fluids and the Reynolds number. The TMR is defined as Eq. (1). Yu et al.

revealed the transitional flow characteristics in the liquid flow passage for movable pintle injectors.⁴⁾ The effect of geometrical change, such as the pintle tip angle, has also been studied.⁵⁾ Lastly, Son et al. proposed a process to design a gas-liquid pintle injector along with well-organized empirical correlations under a wide range of spraying conditions.⁶⁾

$$\text{TMR} = \frac{(\dot{m})_{\text{rad}}}{(\dot{m})_{\text{axi}}} \quad (1)$$

Sakaki et al. investigated a liquid-liquid pintle injector combustion characteristics using liquid oxygen and ethanol in 2014. Experimental studies were performed for both planar and axisymmetric pintle injectors,^{7,8)} using the CH chemiluminescence visualization method. Combustion instabilities and efficiency were measured and analyzed while changing TMR, O/F ratio, and propellant injection velocity.^{9–11)}

In a rocket engine, spraying conditions, spray characteristics, and combustion characteristics are closely inter-correlated. Spray characteristics are determined by spraying conditions and determine the combustion characteristics. In other words, spraying conditions affect combustion characteristics by changing spray characteristics. Combustion is an intensely complicated phenomenon that is not fully determined by single spray characteristics, but the connection between them is crucial.

Most studies on pintle injectors, including those previously mentioned, focused on several design variables or spraying conditions and their correlation to spray characteristics or combustion characteristics. However, there was no strict research approach to evaluate the relation between spray and combustion characteristics in the pintle injector. This is because it is difficult to conduct a well-controlled experiment. For the pintle injector, spray characteristics are interrelated and cannot be controlled independently. Consequently, it is unfeasible to separate the effect of each spray characteristic on the combustion characteristics.

For example, Sakaki et al. obtained a result that shows the c^* efficiency of the axisymmetric combustor decreases as the TMR of the pintle injector increases.⁸⁾ However, in the experiment, the TMR is adjusted by changing liquid oxygen injection velocity, which affected multiple spray characteristics. The study concludes that TMR has a significant effect on c^* efficiency, but it was not possible to clarify whether this is due to an increase in spray angle or a decrease in droplet size.

Separately controlling multiple spray characteristics is essential in a parametric study on the correlation between the spray characteristics and the combustion characteristics. This research aims to decouple two universal spray characteristics, spray angle and droplet size, for a gas-liquid pintle injector with identical O/F ratio and throttling level. In this research, SMD is selected as a representative value of the droplet size. Son et al. have stated that SMD has a positive linear relation with the spray angle and pintle tip angle.⁶⁾ The pintle tip angle in Son et al.,⁶⁾ defined as Fig. 1(b), deflects the radial injection flow downwards as it increases.

Fig. 1. Radial injected flow comparing (a) normal pintle tip, (b) pintle tip with pintle tip angle, and (c) pintle tip with reverse injection effect.

The sensitivity analysis, which is based on the experimental data accumulated, shows that change in the pintle tip angle does not significantly influence SMD, but strongly affects spray angle. In addition, Son et al.⁶⁾ states that decreasing the spray angle at the low throttling level is inevitable. This is because the pintle tip angle is fixed; thus, the downward deflection effect is also fixed.

Inspired by these results, in this study, the idea of ‘reverse injection’ is proposed, which means to deflect the radial injection flow upward using a ‘reverse injection angle,’ as shown in Fig. 1(c). The reverse injection is expected to increase the spray angle while preserving SMD, which is an opposite effect of the pintle tip angle. The underlying idea of reverse injection is to leave the TMR almost unchanged, but increasing the spray angle alone, only by giving small geometrical change in the pintle tip. In addition, to minimize the spray angle decrease at the low throttling level, the ‘reverse injection effect’ is strengthened as the throttling level decreases in the design proposed.

The effect of ‘reverse injection’ is verified by comparing the cold-flow results in the aspect of two spray characteristics—spray angle and droplet size, with those of ‘normal’ pintle injector. Hereby, the ‘normal’ pintle injector stands for the typical pintle injector in which radial flow is injected

without deflection, as shown in Fig. 1(a). The overall injector design is demonstrated first. The ‘reverse injection’ and the ‘normal’ pintle injector shares this design except the pintle tip, as represented in Fig. 1(a) and (c). Then, the spray characteristics for ‘normal’ injector are measured to provide a control group data. In sequence, the theoretical analysis for designing the ‘reverse’ injector is presented. The design point is not only to deflect the liquid flow upward, but also to make the reverse injection effect diminishes with the throttling level increase. Lastly, the spray characteristics of the normal and reverse injectors are compared and analyzed whether the design goal is achieved. Throughout the research, the pintle tip for the normal injector is called ‘normal tip’ and for the reverse injector, ‘reverse tip.’

2. Experimental Setup

2.1. Injector design

For the research, a pintle injector for a 400 N rocket engine using liquid oxygen and gas methane as propellants was designed. The scheme of the pintle injector is shown in Fig. 2(a). Pintle post and pintle tip part, which are enclosed by the red square in Fig. 2(a), is magnified in Fig. 2(b).

The design details are given in Table 1. C_F and c^* are calculated using the NASA CEA code.¹²⁾ In this injector, the liquid is radially injected through the pintle orifice, and the gas is axially injected through the annular orifice. A micrometer head is used to adjust h along with throttling level from 0.1–0.6 mm in microns. G is changed from 0.986 mm to 3.95 mm to adjust the gas injection velocity by replacing

the bottom manifold.

Since the density of gas propellant, which is fuel, under pressurized combustion environment changes greatly, the atmospheric cold test should be planned considering such condition. In addition, the simulant fluids have different density from the real propellants. In this research, to satisfy the similarity between real injection condition and cold-flow test experimental condition, TMR was set to be identical by adjusting the gas flow rate.

TMR is defined as Eq. (1), and can be represented using O/F ratio as following. In this experiment, oxidizer is designed to be injected radially.

$$\text{TMR} = \frac{(\dot{m}u)_{\text{rad}}}{(\dot{m}u)_{\text{axi}}} = \left(\frac{\dot{m}_o}{\dot{m}_f} \right)^2 \frac{A_f \rho_f}{A_o \rho_o} \quad (2)$$

In order to alter the cold-flow test experimental condition TMR same to the real injection condition TMR, below sequences are followed. Same geometrical conditions were assumed for both conditions, and oxidizer mass flow rate was set to be same. The correlation between gas propellant flow rate of real injection condition and experimental condition is obtained as Eq. (3). From calculation the gas flow rate of the cold-flow test, in this experiment air mass flow rate, was selected to be 2.44 times less than the real gas methane mass flow rate.

$$\begin{aligned} \text{TMR}_{\text{real}} &= \text{TMR}_{\text{cold}} \\ \left(\frac{\dot{m}_o}{\dot{m}_f} \right)_{\text{real}}^2 \left(\frac{\rho_f}{\rho_o} \right)_{\text{real}} &= \left(\frac{\dot{m}_o}{\dot{m}_f} \right)_{\text{cold}}^2 \left(\frac{\rho_f}{\rho_o} \right)_{\text{cold}} \\ \dot{m}_{f,\text{cold}}^2 &= \left(\frac{\rho_f}{\rho_o} \right)_{\text{cold}} \left(\frac{\rho_o}{\rho_f} \right)_{\text{real}} \dot{m}_{f,\text{real}}^2 \quad (3) \end{aligned}$$

The injector manifold and pintle tip are machined from polycarbonate and polyether ether ketone (PEEK). However, the pintle post is 3D printed using PA 12 (Polyamide) and the multi-jet fusion (MJF) method. This is due to the importance of geometric tolerance in the pintle injector for the axial symmetry of spraying. Axially 3D printing the pintle post, high perpendicularity and circularity are obtained.

Fig. 2. Pintle injector schematic.

Table 1. Design details of pintle injector.

Thrust, N	400
Chamber pressure, bar	10
Pressure ratio	1000
O/F ratio	3.44
Throttling level, %	20 to 100
C_F	1.9824
c^*	1874.5
$\dot{m}_o$, g/s (at 100% throttling level)	83.40
$\dot{m}_f$, g/s (at 100% throttling level)	24.24
D_{pp} , mm	11
D_{pt} , mm	11
$D_{pt,rod}$, mm	4
L , mm	11
h , mm	0.1–0.6
G , mm	0.725–3.95

2.2. Cold-flow test apparatus

The spray characteristics of the pintle injector are evaluated through an atmospheric cold-flow test, using air and water as simulants for gas methane and liquid oxygen, respectively. In order to control the mass flow rate of air, a mass flow controller (MKP TSC-150, accuracy $\pm 0.2\%$) was used. In order to measure the mass flow rate of water, a mass flow meter (KOMETER KTM-800, accuracy $\pm 0.5\%$) was used.

2.3. Measurement

The spray angle and droplet size were measured from images taken using the shadow method.

2.3.1. Spray angle

To measure the spray angle, the images were taken using a digital camera (Canon EOS 7D, 5184×3456) with Canon EF 24–70 mm lens using and a 40 Hz stroboscope light (SUGAWARA MS-230DA). The camera was set to f/11 and ISO 1000. The apparatus emplacement is shown in Fig. 3.

More than 50 images were taken for each case. To process the images, the region of interest in each image was cut and averaged. Next, following the process represented in Fig. 4, the averaged image (Fig. 4(a)) is first binarized by a threshold, to detect the spraying area (Fig. 4(b)). At the edge of the spraying area, an appropriate sample section was selected and first-order approximated to obtain spray half-angle from the left and right sides. The sample sections selected are marked by the thick line in Fig. 4(c)—left with blue and right with red. Spray angle is defined as the sum of left and right spray half-angles.

For each case, the length required for the liquid and gas flows to interact and converge is different. Calculating the spray angle for each case using a uniform standard was considered illogical, and different sample parts were selected for each throttling levels and cases with different gap distances. However, to compare the normal and reverse tip data, the same criterion was applied for both groups.

2.3.2. Droplet size

Sauter mean diameter (SMD) was chosen as the representative value of droplet size. The images were taken using a high-speed camera (Photron FASTCAM SA5, 1024×1024) aided by a long-distance microscope (LDM, LaVision QM1) and a 50 Hz stroboscope light. The apparatus for high-speed imaging is shown in Fig. 5. The spatial resolution for these experiments was $4.67 \mu\text{m}/\text{pixel}$. The camera was set to f/8.7 with a depth of field $155 \mu\text{m}$ and a working distance of 560 mm.

More than 150 images were taken for each case and processed as Fig. 6. From each image, several droplet candidates were detected. Each candidate image's judging constant M was calculated based on its area and perimeter using Eq. (4). The judging constant M indicates how close the droplet image is to a perfect circle ($M = 1$). In this research, those having a M larger than 0.7 were considered true droplets. Each droplet's diameter was calculated based on each droplet's area using Eq. (5). Finally, the SMD for each case was calculated using Eq. (6).

Fig. 3. Spray angle measurement setup.

(a) Averaged spray image

(b) Binarized image

(c) Spray half-angle calculated for each side

Fig. 4. The image processing procedure for spray angle calculation.

Fig. 5. SMD measurement setup.

Fig. 6. The image processing procedure for SMD measurement. Original image (a) was obtained in grayscale and binarized (b), where droplets were detected and judged from each dark bulk area and perimeter. The result is shown in (c).

Fig. 7. SMD measuring point.

$$M = \frac{4\pi A}{p^2} \quad (4)$$

$$D = 1000 \sqrt{\frac{4A}{\pi}} \quad (5)$$

$$\text{SMD} = \frac{\sum D_i^3}{\sum D_i^2} \quad (6)$$

Droplet size is highly sensitive characteristic and is affected by position from which it is measured. In this research, SMD was measured at the right edge of the spray, 20 mm axially away from the end of the pintle tip as shown in Fig. 7. The region of interest was about 4.78 mm by 4.78 mm square and 1024 pixels for each edge.

3. Normal Tip

3.1. Cold-flow experimental cases

Experiments with different annular orifice gap sizes for three throttling levels were performed for a pintle injector equipped with a normal tip; the details of each case are shown in Table 2. Spray angle and SMD were measured for each case. For the 20% throttling level group, however, the analysis excludes Cases C–F, in which atomization did not occur properly. In order to compensate for the lack of data points in the 20% throttling level group, Case X with a 0.725 mm annular orifice gap is added.

For a liquid-liquid pintle injector, it is recommended to select a TMR value near unity for design based on design experience related to the spray angle.¹³⁾ However, this was not true for the gas-liquid pintle injector. The experiment and simulation conducted by Cheng et al. shows that a liquid-liquid pintle injector's spray angle becomes approximately 120 deg when the TMR is near unity; that is, with G of 1.05 mm and h of 0.60 mm.¹⁴⁾ In the gas-liquid pintle injector, under a throttling level condition of 100%, where h is 0.6 mm, G must be about 4.88 mm to meet unity TMR. However, under this design condition, the spray angle becomes near 180 deg, which is inappropriate. The gas-liquid pintle injector turned out to have a spray angle of 140 deg when the TMR is approximately 0.747 and having a G of 3.95 mm, which is Case F in Table 2. Since the recommended TMR value for the liquid-liquid pintle injector was based on its spray angle (e.g., approximately 120 deg), the upper limit of the TMR for experimental cases in Table 2 are selected to have a spray angle under 140 deg. The lower limit of the TMR was selected to meet the mechanical ma-

Table 2. Experimental cases and TMR for each case.

	TMR	20%	60%	100%
	h	0.1	0.35	0.6
Case	G			
A	0.986	0.880	0.248	0.145
B	1.21	1.100	0.309	0.181
C	1.835	—	0.493	0.288
D	2.6	—	0.741	0.433
E	3.3	—	0.988	0.577
F	3.95	—	1.237	0.722
X	0.725	0.633	—	—

Fig. 8. Spray angle and TMR relationship of the normal tip.

Fig. 9. SMD and We relationship of the normal tip.

chining error limit of G in manufacturing process.

3.2. Normal tip results

Both spray angle and SMD raw images of the normal tip are shared with previous work.^{15,16)} However, different methodology was applied in determining the spray angle, obtaining different data. Figures 8, 9, and 10 represent the spray angle and SMD of the pintle injector with a normal tip for each throttling level.

$$\text{We} = \frac{\rho_{\text{axi}}(u_{\text{axi}} - u_{\text{rad}})^2 \cdot h}{\sigma_{\text{rad}}} \quad (7)$$

Figure 8 shows that the spray angle has a positive correlation with the TMR, while it seems to have an upper limit. This is because the maximum spray angle of the normal tip cannot exceed 180 deg. From Fig. 9, a negative correlation

Fig. 10. SMD and spray angle relationship of the normal tip.

between We and SMD can be observed. The We number for the normal tip is defined in this research as Eq. (7), using h as the characteristic length. The results of Fig. 9 are straight forward for the gas-liquid pintle injector, since the gas injection velocity strongly affects the We number, and at the same time, works as a main factor of atomization. Figure 10 represents a positive correlation between the spray angle and SMD. Additionally, in a low throttling level, SMD is larger compared to other throttling levels for the same spray angle. This means that the throttling engine design should satisfy a wide change in spray characteristics, either spray angle or SMD.

The idea of reverse injection is to increase the spray angle while preserving the SMD. If properly designed, with reverse injection, it is possible to narrow down the spray angle varying range for a throttling rocket engine. To achieve this goal, the reverse injection effect should be maximized at the lowest throttling level and diminished at the highest.

4. Reverse Tip

4.1. Physical analysis of reverse injection

In the reverse injection case, TMR should be newly defined, considering the axial component of radial flow. Figure 11 demonstrates the reverse injection flow diagram. Hereafter, the newly defined TMR for reverse injection flow is $rTMR$, and defined using Eq. (8).

Since the mass flow rate of radial flow is equal for both normal and reverse tips, the radial injection velocity of the liquid is given as follows.

$$u_{r,rad} = \frac{\dot{m}}{2\pi \cdot D_{pt} \cdot \rho_{liquid} \cdot h_r} = \frac{h \cdot u_{n,rad}}{h \cdot \cos \theta} = \frac{u_{n,rad}}{\cos \theta}$$

Furthermore, it is assumed that the axial flow is not affected by the reverse injection. Therefore,

Fig. 11. Reverse injection flow diagram.

Fig. 12. Design of the reverse pintle tip.

$$\begin{aligned} rTMR &= \frac{\text{radial flow momentum (r.f.m.)}}{\text{axial flow momentum (a.f.m.)}} \\ &= \frac{\text{r.f.m. of liquid}}{\text{a.f.m. of gas} - \text{a.f.m. of liquid}} \\ &= \frac{(\dot{m}u_r)_{rad} \cos \theta}{(\dot{m}u_n)_{axi} - (\dot{m}u_r)_{rad} \sin \theta} \\ &= \frac{(\dot{m}u_n)_{rad} \frac{\cos \theta}{\cos \theta}}{(\dot{m}u_n)_{axi} - (\dot{m}u_n)_{rad} \frac{\sin \theta}{\cos \theta}} \\ rTMR &= \frac{(\dot{m}u)_{n,rad}}{(\dot{m}u)_{n,axi} - (\dot{m}u)_{n,rad} \tan \theta} \end{aligned} \quad (8)$$

In the same context, the We number should also be redefined. This is named rWe , and defined using Eq. (9).

$$rWe = \frac{\rho_{axi}(u_{axi} - u_{r,rad} \cdot \cos \theta)^2 \cdot h}{\sigma_{rad}} \quad (9)$$

4.2. Reverse tip design

The hypothesis was that reverse injection would increase the spray angle without changing the droplet size by deflecting the liquid injection direction upward. The normal tip in Fig. 1(a), is designed to inject the liquid flow radially, which is the control case in this research. The design of the reverse tip is given in Fig. 12, and its detailed values are given in Table 3.

The main idea of this research is to provide and validate a method to control one of two spray characteristics while changing the other. The use of reverse injection is proposed

Table 3. Final design parameters for the reverse tip.

d	2.80 mm
d^*	0.25 mm
r	0.4 mm
Reverse injection slope	20 deg

Table 4. Experimental cases and rTMR for each case.

rTMR		20%	60%	100%
h		0.1	0.35	0.6
Case	G			
A	0.986	0.944	0.247	0.144
B	1.21	1.203	0.310	0.180
C	1.835	—	0.498	0.287
D	2.6	—	0.756	0.431
E	3.3	—	1.020	0.576
F	3.95	—	1.290	0.721
X	0.725	0.663	—	—

Fig. 13. Water-only reverse injection spray images.

to increase the spray angle while preserving the droplet size. To narrow down the spray angle design range in a throttling engine, as explained in previous section with Fig. 10, a reverse tip was designed to have maximum reverse injection angle in the lowest throttling level, while having a 0 reverse injection angle at the full throttling level. This was realized by designing a groove, marked with the red line in Fig. 12, in the appropriate size so that its depth (0.06 mm) becomes negligible during 100% throttling ($h = 0.6$ mm), but cannot be ignored at a lower throttling level ($h = 0.35$ mm/0.1 mm).

4.3. Reverse tip results

Experiments were performed for the reverse tip through cases in Table 2, and the results were compared to those of the normal tip. For the 20% throttling level group, cases in which atomization did not happen were omitted from analysis (C–F) and Case X was added; the same as for the normal tip. With rTMR newly calculated, the experiment cases are presented in Table 4.

4.3.1. Reverse injection effect

To evaluate the pure effect of reverse injection on the radial flow, the spray angle without axial flow was measured for each throttling level. The results are shown in Fig. 13.

The 100% throttling level shows no reverse injection, while the 20% and 60% throttling levels show approximately 24.1 deg and 13.8 deg in reverse injection angle, θ , respectively.

(a) 20% throttling level

(b) 60% throttling level

(c) 100% throttling level

Fig. 14. Spray angle comparison for the reverse and normal tips.

4.3.2. Spray angle

Figure 14 represents the spray angle for the reverse tip, along with that of the normal tip. In Fig. 14, normal tip data is marked as filled squares and reverse tip data is marked as empty squares. For the 20% throttling level, in which the reverse injection effect is maximum, the spray angle is increased an average of 20.1 deg. For the 60% throttling level, where there was little reverse injection effect, the spray angle increased an average of 9.3 deg. For the 100% throttling level, in which there was no reverse injection effect, the result was identical, or even inferior, to that of the normal tip. Exact measured values are shown for the 20% throttling level in Fig. 14(a) in order to clearly represent the maximized reverse injection effect.

Fig. 15. SMD and rWe relationship of the reverse tip and normal tip.

Fig. 16. SMD and spray angle relationship of the reverse tip and normal tip.

The reverse injection effect is not only affected by the throttling level, but also by rTMR, altered by G . For small rTMR, in which G is small and the gas flow momentum is substantial, the reverse injection effect is relatively weak. For cases where rTMR is larger, where G is large and the gas flow momentum is small, the reverse injection effect was emphasized. This is because the axial momentum generated from the liquid flow's reverse injection, can have a stronger influence on the denominator term of rTMR (Eq. (8)) as the axial momentum of the gas flow decreases.

4.3.3. Droplet size (SMD)

The relationship between SMD and We for each reverse tip case is represented in Fig. 15, along with the data for the normal tip. The SMD data for the reverse tip was nearly identical to that of the normal tip. The correlation between SMD and We in Fig. 15 could be represented using an empirical equation, Eq. (10), with $R^2 = 0.92$. Usually, We is known as main factor to determine the SMD, since it is strongly related to a shear breakup mechanism. The change in We as the result of applying reverse injection, as defined in Eq. (9), is negligible. This is the first reason why SMD is not affected by reverse injection. The second, and more important, reason is that the pintle injector has basically an impinging injector breakup mechanism that does not rely heavily on shear breakup. Since reverse injection only deflects the radial flow and slightly changes the impinging environment, it is logical to state that reverse injection does not alter the overall atomization process, which is dominated by collision.¹³⁾

$$\text{SMD } (\mu\text{m}) = 430.80e^{-\text{We}/74.55} + 123.21 \quad (10)$$

The relationship between SMD and spray angle for each reverse tip is shown in Fig. 16, along with the data of the normal tip. For the 20% throttling level, the SMD of the reverse tip is similar to that of the normal tip, while the spray angle of the reverse tip increases compared to the normal tip. The same applies to the 60% throttling level, in which the reverse injection effect is small, thus observing only a minor increase in the spray angle. For the 100% level, in which the reverse injection effect is nonexistent, there is no difference in SMD

Fig. 17. How reverse injection controls both spray characteristics.

and spray angle. Therefore, it is reasonable to state that reverse injection preserves SMD and increases the spray angle, thus the hypothesis is proven to be true.

Although the feasibility of adjusting the SMD without changing the spray angle is not proven in the experiment directly; however, following the logic presented in Fig. 17, it might be possible to do so.

Assume Fig. 17 represents a relationship between SMD and spray angle for any pintle injector, which is obtained from experiments. Cases α and β stand for different spraying conditions with a different spray angle and SMD. If reverse injection is applied to Case α shown in Fig. 17, the spray angle will increase, and Case α will shift to Case α^* as shown. Case α^* has the same spray angle, but a different SMD than Case β , under different spraying conditions with Case α . It may be illogical to state that reverse injection can also reduce SMD while preserving the spray angle, but it is undeniable that reverse injection introduced a breakthrough by controlling one of two spray characteristics as a manipulation variable. Sample datasets for this logic are given in Table 5, and are marked with arrows in Fig. 16. Capital letters stand for cases in Tables 2 and 4, while subscripts represent the throttling level and whether the data point is from a normal tip or

Table 5. Example datasets for Fig. 17, from Fig. 16.
(Decoupling spray characteristics—spray angle and droplet size)

Case	α	β	α^*
Group 1	$A_{60\%,n}$	$B_{60\%,n}$	$A_{60\%,r}$
α (deg)	56.0	63.3	62.6
SMD (μm)	227.1	259.9	233.5
Group 2	$D_{60\%,n}$	$E_{60\%,n}$	$D_{60\%,r}$
α (deg)	129.1	137.0	136.3
SMD (μm)	503.3	562.8	507.2

Table 6. Examples for spray angle change range decrease in throttling.

$\dot{m}$	20%	60%	100%	K
Normal	$B_{20\%,n}$	$D_{60\%,n}$	$F_{100\%,n}$	
α (deg)	90.0	129.1	139.2	21.8
SMD (μm)	501.4	503.3	502.9	0.2
Reverse	$B_{20\%,r}$	$D_{60\%,r}$	$F_{100\%,r}$	
α (deg)	111.5	136.3	136.8	11.3
SMD (μm)	489.6	519.4	489.0	3.5

reverse tip.

The reverse tip is designed to have no reverse injection effect at the 100% throttling level, but to maximize it at the 20% throttling level. This means reducing the spray angle change range while throttling from 100% to 20%. From the arrow-marked data points of Fig. 16, by comparing the three normal tip cases (i.e., $B_{20\%,n}$, $D_{60\%,n}$, $F_{100\%,n}$) with reverse tip cases (i.e., $B_{20\%,r}$, $D_{60\%,r}$, $F_{100\%,r}$), the decrease in spray angle change range can be confirmed. The details of the data points are shown in Table 6. K , in the right column of Table 6, is defined using Eq. (11), representing how much data points are scattered. There is little change in the K of SMD between the normal and reverse tip data. However, the K of spray angle decreased significantly from the normal tip to reverse tip. This indicates that application of the reverse tip can narrow down the spray angle change while throttling from 100% to 20% without changing the SMD. Narrowing the range of spray angle variance for a throttleable engine can improve several launch vehicle properties: shortening the length of the combustion chamber, and improving the combustion efficiency, and mass fraction of engines.

$$K = \frac{\text{Standard deviation}}{\text{Average}} \cdot 100 \quad (11)$$

5. Conclusion

In this study, the goal was to control one spray characteristic of a pintle injector while leaving the other unchanged. Spray angle and droplet size were chosen as the target spray characteristics. The idea of reverse injection was proposed, realized and verified through several cold-flow tests and shadow method imaging. The experiment was based on comparing the spray characteristics of the normal and reverse tips for various cases and throttling levels. As a result, the spray angle increased for the reverse tip while the droplet size re-

mained nearly unchanged compared to those of the normal tip. Additionally, within the same throttling level, the reverse injection effect increased as rTMR increased. Two major effects of reverse injection could be discovered from experiments. First, by applying reverse injection, two major spray characteristics of pintle injector—spray angle and droplet size, SMD, were decoupled. The first effect was the goal of this study and gave a breakthrough to investigate the effect of each spray characteristic independently, which was not possible in the past. Controlling the droplet size equally while changing the spray angle was possible by applying reverse injection design to the normal tip. Though it was not explicitly obtained, data sets with the same spray angle and different droplet size were also observable. Thus the first effect of the reverse injection enables the parametric study on the correlation between spray characteristics and combustion characteristics. The second effect is to narrow down the spray angle change during throttling by applying reverse injection. This was possible because the reverse injection can increase the spray angle at a low throttling level without changing that at a high throttling level. The reverse injection may contribute to shortening the combustion chamber in a pintle injector throttleable engine, which will improve the mass-fraction of a launch vehicle.

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