Study on atomization characteristic of dual-orifice pressure-swirl injector

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Abstract. Fuel atomization greatly affects the combustion efficiency and uniformity of gas generator, therefore investigation on spray characteristics of injector is significative. In the present study, dual-orifice pressure-swirl injectors were designed and manufactured to meet the practical needs of mass flow rate and combustion performance of gas generator; water was used as the simulant medium for fuel, and Malvern optical instrument and SLA camera were applied to investigate the atomization characteristics of injectors. The results show that the mass flow rate, spray cone angle and Sauter Mean Diameter (SMD) all satisfy the design index request; the Sauter Mean Diameter decreases with the increase of injection pressure drop, but the decreasing tend becomes slow; when the spray develops to a certain position of injector exit, the Sauter Mean Diameter of axial sections keeps constantly.

1. Introduction
Gas generator is a kind of device which obtains high temperature gas by burning propellant. It is widely used in aerospace engineering, petroleum industry, automobile industry, ocean transportation and other fields, such as scramjet ground test heating system, negative pressure/vacuum pumping system, laser pressure recovery system and marine gas turbine [1-12], etc.

As one of the key components of gas generator, fuel injector greatly affects combustion performance of gas generator, such as combustion stability and combustion uniformity. Good atomization performance of fuel injector can reduce fuel droplet diameter, increase fuel evaporation rate and combustion rate, increase combustion efficiency, thus improving ignition and flame stability, and providing better outlet temperature field distribution.

At present, various kinds of injectors including straight flow injector and pressure-swirl injector have been applied to the gas generator [13, 14], and the latter is widely used because of its good atomization performance. However, lacking of perfect theoretical analysis model, the existing researches on the atomization performance of the pressure-swirl injector depend mainly on experiment means of measuring the spray cone angle and droplet size distribution parameters [15, 16], etc.

The dual-orifice pressure-swirl injector, which is the improved single-orifice pressure-swirl injector, has been a hot spot in the research of pressure-swirl injector. Its prominent advantage lies in wide range fuel adjustment, and obtaining good atomization quality under low flow rate condition, thereby meet the stable combustion and complete combustion for gas generator can be met with various working conditions [17].
According to the working characteristics of a certain type of gas generator, dual-orifice pressure-swirl injectors were designed and processed in this paper on the basis of comprehensive analysis of the advantages and disadvantages of various injector schemes. With the help of SLR camera, Malvern optical instrument, etc., related researches are carried out, and preliminary results are obtained.

2. Injector Type
The dual-orifice pressure-swirl injector works as follows, shown in Fig. 1: when air pressure is relatively low, atomization depends mainly on the fuel supply pressure; under the condition of higher air pressure, primary spray is realized by the action of fuel supply pressure, and then with the effect of the first stage swirler and secondary swirler, the secondary spray gets achieved; fuel spray is driven forward by the airflow generated by the two stage swirler, and fuel film forms on the inner surface of venturi; at last, the two airflow produce shear breaking for fuel film at the venturi exit. Test conditions limited, single-phase with liquid spray test was carried out in this article.

Design of the injector of this paper can be realized by two single fuel injector designs, and the designed dual-orifice pressure-swirl injector is shown in Fig. 2. The injector is mainly composed of shell, swirl core, main injection jet and secondary injection jet, etc. Among them, the injector shell is welded with the inlet pipe, connected with main injection jet by screw thread, thus forming the isolated channel between main circuit and secondary circuit; the function of swirl core is to generate tangential velocity for fuel of secondary circuit; the secondary injection jet is used to produce tangential velocity for main circuit and accelerate the injection channel fuel for secondary circuit; the main injection jet forms the fuel-accelerated injection channel for main circuit, and the equispaced orifices around are used to blow down the carbon deposition.

3. Testing System
Due to the limitation of the test conditions, there was no back pressure on the downstream of the injector, which means the atomization test was carried out at atmospheric pressure. The main test
system, including test objects, spray stand, supply system, measure & control system and measuring equipment (mainly including SLR camera, high precision electronic scale and Malvern optical instrument), and the schematic diagram and flow diagram of spray test are shown in Fig. 3, Fig. 4, respectively.

![Figure 3. Schematic diagram of spray test platform](image1)

![Figure 4. Flow diagram of spray test system](image2)

### 3.1. Supply, measure and control system

Considering the safety factors, water was used as the simulant medium for fuel. The supply system, which can smoothly supply simulant liquid and extrusion gas, mainly including:

**Extrusion gas path**: filter, manual stop valve, manual reducing valve, manual stop valve and fast acting valve were arranged in the pipeline.

**Liquid tank**: the tank top was equipped with refueling port, manual inlet valve, extrusion gas inlet, safety valve and manual gas release valve, and a liquid outlet was arranged in the bottom of the tank.

**Liquid path**: the discharge valve, manual stop valve, filter and fast acting valve were set up in turn.

Measure and control system were mainly responsible for spray operation sequence control, safety interlock, parameter measurement and data processing. The control objects included pressure relief valve, fast acting valve and other valves, and they were configured with signal feedback of opening and closing. In addition, measure and control system measured and recorded the pressure of each measuring point during the test. The pressure sensor adopted the pressure-resistance pressure transmitter of Mike sensor company, with the maximum response frequency of 30kHz and the measurement accuracy of 0.5% FS (full scale).
3.2. Measuring equipment

The measuring equipment used in the experiment mainly includes SLR camera, high precision electronic scale and Malvern optical instrument. Among them, the SLR camera was used to shoot the injector spray field and get the spray cone angle after post-proposing. The high precision electronic was applied to weigh mass flow rate, and the final result was the average of the 3 groups in the same working condition.

Malvern optical instrument was used for measuring the size distribution of spray and smoke in real time [18]. It provides the data required to fully understand spray and atomization processes. It will: measure across a wide size range (0.1 microns ~ 2000 microns) without requiring constant optics changes; resolve rapid changes in droplet size over time, by measuring up to 10,000 measurements a second; deliver accurate, concentration-independent results using a patented multiple scattering analysis; characterize wide spray plumes without risking optical contamination; simply reveal the dynamic changes in spray particle size through its unique size history analysis software. It mainly consists of the following parts (as shown in Fig. 5): transmitter module, receiver module and optical bench, etc. Among them, the transmitter module which contains the collimated laser light source used to illuminate the spray during a measurement. The receiver module which can hold one of two lenses (300mm or 750mm) which focus any light scattered by the spray onto a series of detectors. These detectors accurately measure the intensity of light scattered by the spray droplets over a wide range of angles. The optical bench which ensures the transmitter and receiver are aligned. The length of this can be changed in order to fit with different applications, with the longest bench being 2.5m long.

![Figure 5. Component diagram of Malvern optical instrument](image)

4. Experimental Results and Analysis

4.1. Discharge coefficient

Discharge coefficient refers to the ratio between actual mass flow rate and theoretical mass flow rate. The actual flow rate is obtained by experiments, and the theoretical flow rate can be calculated from continuity equation and Bernoulli equation. Calculation formula for liquid flow rate as shown below:

$$m = C_A \sqrt{2 \rho \Delta P}$$  \hspace{1cm} (1)

Where $m$ refers to liquid flow rate; $C_A$ is discharge coefficient; $A$ is flow area; $\rho$ refers to density of working fluid; $\Delta P$ is injection pressure drop. Therefore, discharge coefficient of liquid can be calculated from the following formula:
The curve of injector flow rate with injection pressure drop is shown in Fig. 6. It can be seen that the flow rate and injection pressure drop basically change in exponential form, which is consistent with the flow rate calculation formula.

\[ C_A = \frac{\dot{m}}{A \sqrt{2\rho \Delta P}} \]  

(2)

![Figure 6. Mass flow rate with injection pressure drop](image)

Fig. 7 shows the curve of discharge coefficient with the change of injection pressure drop. Discharge coefficient remained at around 0.22 within the pressure drop range in test. Due to the error caused by injector processing and flow rate measurement, discharge coefficient fluctuates within a narrow range. The overall trend shows that the discharge coefficient is less affected by injection pressure drop.

![Figure 7. Discharge coefficient with pressure drop](image)

The relationship between the mass flow rate and injection pressure drop is presented in Table 1, as well as error analysis. Mass flow rate is proportional to the 0.5 power of injection pressure drop (R-square refers to fitting parameter, the closer that this value is to 1, the better fitting effect is). This conclusion is basically consistent with the theoretical result of formula (1).
Table 1. Fitting function of mass flow rate with pressure drop

| Parameters | Fitted value | R-square |
|------------|--------------|----------|
| A          | 72.574       | 0.995    |
| B          | 0.5          |          |

4.2. Spray cone angle

Spray cone angle is an important factor affecting the atomization quality. Larger angle is advantageous to the gas-liquid mixing effect, promoting the primary and secondary spray, obtaining smaller and more uniform atomization particles, which benefits the gas generator combustor lean blowout. When the spray cone angle is too large, fuel tends to spray into the combustion liner wall in the combustion chamber, producing carbon deposition, which is not conducive to the combustion chamber life. So the proper spray cone angle is very important to the combustion organization of gas generator.

Spray cone angle is obtained by shooting spray field with SLR camera after post-proposing. Normal spray field at 2.5MPa is shown in Fig. 8. The spray is divided into two layers with obvious boundary, and the corresponding cone angles are 105.5 degrees and 70.9 degrees, respectively. This is consistent with design value (104 degrees and 70 degrees respectively).

However, due to reasons such as machining precision, individual injector appears splitting beam, inapparent boundary and disalignment between internal and external spray. Fig. 9 shows the abnormal spray field with splitting beam and inapparent boundary. The reason for splitting beam is that injector processing is not enough refined, thus burr exist on the injector inner surface. Because of the excessive thermal deformation brought by improper temperature control during welding, the gap between the main injection jet and the secondary main injection jet is too small, resulting in no layer-built.

4.3. Sauter mean diameter (SMD)

Injector particle diameter usually refers to the SMD (Sauter mean diameter) for gas generator. Its physical meaning is the same size with the diameter of droplets instead of actual droplets, keeping the surface area to volume ratio the same as the real droplet group. SMD is an important index to evaluate the atomizing performance of injector, and the smaller the SMD value is, the better the atomizing performance of injector is.
SMD value with different injection pressure drop as shown in Fig. 10. SMD value decreases as the injection pressure drop increases, and the reason is that film thickness at injector exit decreases gradually as the injection pressure drop increases. Moreover, A. K. Jasuja [19] has obtained the relationship about $SMD \propto h^{0.4}$, and $h$ refers to film thickness, hence the SMD value decreases gradually. However, this effect is obvious at the beginning, when the pressure drop increases to 1.5MPa, with the increase of injection pressure drop, the tendency to be gradual.

Z.T. Kang [13] showed that, with the increase of distance from injector exit, SMD value decreases gradually. The reasons are as follows: the rotating conical liquid sheet produced by the pressure-swirl injector, interaction with the ambient air, keeps growing and broken into liquid silk; then broken into droplets under the action of aerodynamic force; secondary spray of the large droplets achieved, resulting in small droplets. However, when the distance away from injector exit reaches to a certain value, which is to fully atomized, SMD value tends to the same order of magnitude, and differs very little, as shown in Fig. 11 (measuring height refers to the distance from injector exit to the laser axis center). With the increase of injection pressure drop, the tendency and value of SMD in each cross section show the same.

![Figure 10. SMD with pressure drop](image)

![Figure 11. SMD with pressure drop of different cross-section](image)
5. Conclusion
In order to ensure the uniformity and stability of the combustion of the air/ethanol gas generator, dual-orifice pressure-swirl injectors were designed in this paper. Spray characteristics of injectors were measured by SLR camera and Malvern optical instrument. The results are summarized as follows:

1. Mass flow rate of designed injector meets the target, and the spray field has obvious layer; moreover, the internal and external cone angle are consistent with the design goal.

2. Discharge coefficient of injector remains unchanged at different injection pressure drops.

3. SMD value decreases with the increase of injection pressure drop, and the trend of decrease is obvious at the beginning. However, when the injection pressure drops up to 1.5MPa, the tendency tends to be stable.

4. When fully atomized, the injector SMD value is essentially constant as the distance from the injector exit increases.

Acknowledgments
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