Experimental study on atomization characteristic of tripropellant gas-liquid coaxial injector

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Abstract. Tripropellant gas-liquid coaxial straight flow injector was designed and manufactured to meet the practical needs of combustion air heater (CAH). Water and air are used as the simulant, and Malvern optical instrument and Single Lens Reflex (SLR) camera are applied to investigate the effect of recess size and the circular seam size of air on the discharge and spray characteristics. The results show that the discharge characteristic remains basically the same in different recess sizes; the gaseous phase significantly improves the atomization performance, as well as increases the spray cone angle; the recess size of injector and the circular seam size of air basically have no impact on the spray cone angle; the Saunter Mean Diameter (SMD) of particle is influenced by the gas pressure drop, the recess size of injector and the circular seam size of air.

1. Introduction
Combustion air heater heats air directly with a fuel-oxidizer reaction. Fuel is burned in the air stream in a combustor similar to a ramjet combustor. The exhaust gases are used for ramjet testing after the consumed oxygen is replenished. It is widely used in aerospace engineering, such as scramjet ground test heating system [1-3].

As one of the key components of combustion air heater [4], its function lies in mixing the fuel and oxidant thoroughly by atomization, thus producing highly efficient and stable combustion. At present, various kinds of injectors including pressure-swirl injector and straight flow injector, etc. have been applied to the combustion air heater [5-6], and the coaxial straight flow injector is widely used due to its broad turndown ratio. Liquid fuel and oxidizer into the combustion chamber through the injector spay, then atomization, evaporation and mixing the uniformity of mixture directly affects the combustion stability and combustion efficiency, thereby affecting the quality of nozzle outlet flow field of air heater [7].

With the wide application of coaxial straight flow injector in the field of combustion air heater and liquid rocket engine, the experimental research of coaxial injector is quite common[8-11]. Zhang et al. [8] presented the atomization characteristic is better with the increase of recess size of injector. Sun et
al. [9] concluded that the coexistence of gas liquids has little influence on the discharge characteristic of gas-liquid coaxial straight flow injector. Tien et al. [10] found that a suitable recess size will help achieve good atomization characteristic and proper discharge performance. With the help of high pixel camera, Malvern optical instrument, etc. related researches of tripropellant (alcohol, oxygen and air) coaxial straight flow injector are carried out in this paper, and preliminary results are obtained.

2. Experimental methods

2.1. Experimental facilities

As shown in Fig.1, the experimental apparatus are composed of a propellants feed system, a tripropellant coaxial injector, a spray collector, a SLR camera and a Malvern optical instrument system. Considering the safety factors, the experiment was simplified as follows: water is used as the simulant medium for fuel; air is used as the simulant medium for oxygen.

Spray experiments were conducted at atmospheric pressure, with filtered water and dry air supplied through a pressurized feed system. Pressure sensors with an accuracy of 0.5% FS were used to measure the pressure in liquid and gas manifold. Liquid mass flow rate was measured by a turbine flow meter with an accuracy of 0.5% FS. The volume flow rate of gaseous propellant was measured by a turbine flow meter with an accuracy of 0.5% FS. To calculate the mass flow rate of gaseous propellant, the pressure and temperature of gas at the inlet of the gas flow meter were also measured.

Schematic of the tripropellant coaxial injector is featured in Fig.2 (named Case00). The liquid alcohol is injected through the center hole; the dried oxygen and air are injected through the middle circular seam and the outside circular seam, respectively.

![Flow diagram of spray test system](image1)

![Schematic of injector](image2)

Figure 1. Flow diagram of spray test system

Figure 2. Schematic of injector

2.2. Experimental conditions

The injection pressure drops and the corresponding mass flow rates of gas and liquid in these tests were listed in Table 1. Moreover, the effect of structural parameters of injector on atomization characteristics were studied in this paper, the comparison cases with various parameters are shown in Table 2.
2.3. Experimental techniques
A SLR camera was used to shoot the injector spray field and get the spray cone angle after post-
proposing. Moreover, A Malvern optical instrument was employed for measuring the size distribution
of spray in real time [12].

Table 1. Experiment parameters of injector

| Component | Mass flow rate(kg/s) | Pressure drop(MP) |
|-----------|----------------------|-------------------|
| Air       | 0.022~0.088          | 0.5~1.95          |
| Oxygen    | 0.0065~0.016         | 0.75~1.95         |
| Alcohol   | 0.0096~0.0145        | 0.68~1.55         |

Table 2. Cases with different sizes

| Variable name                  | Case No.         | Size(nondimensionalize) |
|--------------------------------|------------------|-------------------------|
| Reference case                 | Case00           | H; L                    |
| Recess size                    | Case01           | (H-3.5); L              |
|                                | Case02           | (H+1.5); L              |
| Air circular seam size         | Case03           | H; (L+0.85)             |
|                                | Case04           | H; (L+1.7)              |

3. Results and discussions

3.1. Discharge characteristic
Discharge coefficient is an important parameter to evaluate the discharge characteristic. The liquid
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:

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

Where $\dot{m}$ refers to liquid flow rate; $C_A$ is discharge coefficient; $A$ is flow size; $\rho$ refers to
density of working fluid; $\Delta P$ is injection pressure drop. Therefore, discharge coefficient of liquid can
be calculated from the following formula:

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

Sonic phenomenon existed because of the gas compressibility, thus calculation for gas mass flow
rate should be divided kind of cases, namely, sonic condition and subsonic condition. Calculation
formula as shown below:

$$\dot{m} = \begin{cases} 
C_A P \sqrt{\frac{2k}{(k-1)RT} \left( \frac{P}{P^*} \right)^{\frac{k}{k-1}} - \left( \frac{P}{P^*} \right)^{\frac{k}{k-1}}} & \text{if } \sigma_{cr} < \frac{P}{P^*} \leq 1; \\
C_A P \sqrt{\frac{k}{RT} \left( \frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} & \text{if } \frac{P}{P^*} \leq \sigma_{cr}. 
\end{cases}$$  \hspace{1cm} (3)

$$\sigma_{cr} = \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}}$$
Where $P$ refers to the gas total pressure; $\sigma_{cr}$ is critical pressure ratio; $P_e$ refers to the outlet pressure; $k$ is the specific heat ratio; $R$ refers to the gas constant; $T$ is the total temperature.

The ratio of pressure before injecting and combustor pressure is obviously greater than the critical value, thus the gas in the injector is not sonic under the condition of hot test. However, the downstream pressure of the injector is atmospheric pressure under the condition of cold test. Therefore, the gas discharge coefficient can be calculated from the following formula:

$$ C_A = \frac{\dot{m}}{\left(\frac{k}{RT} \left(\frac{P_e}{P} \right)^{\frac{k}{k-1}}\right)^{\frac{k}{k-1}}} $$

Fig. 3 shows the curve of discharge coefficient of alcohol hole with various injection pressure drops. Discharge coefficient remains at around 0.74 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. With the increase of pressure drop, the friction force between the spray air and recess section increases, resulting in the loss of discharge characteristic, thus the discharge coefficient of air circular seam decreases with the increase of pressure drop, as shown in Fig. 4.

![Figure 3. Discharge coefficient of alcohol hole with pressure drop](image)

![Figure 4. Discharge coefficient of air circular seam with pressure drop](image)

Discharge characteristics of cases with different recess sizes under various air pressure drops are shown in Fig. 5 and 6, keeping the injection pressure drop of alcohol and oxygen constant. As shown from the curves, discharge characteristics of cases behave very similarly.
3.2. Spray cone angle
For detailed research, spray cone angle of monopropellant, bipropellant and tripropellant were photographed and analyzed, and the specific results are as follows.

Fig. 7 shows the spray fields of Case00 under different oxygen pressure drops on the condition of bipropellant, leaving the alcohol pressure drop unchanged. It can be seen that the addition of gas component obviously expands the atomization angle, thus improving the jet atomization. In addition, the spray cone angle increases from 17.4 degree to 21 degree when the oxygen pressure drop changed from 0.74 MPa to 1.3 MPa.

![Spray field of bipropellant with different oxygen pressure drop](image1)

(a) 0.74Mpa  
(b) 1.3Mpa

**Figure 7.** Spray field of bipropellant with different oxygen pressure drop

On the condition of constant alcohol pressure drop, the spray fields of Case00 under different air pressure drops are shown in Fig. 8. With the increase of pressure drop, the action of the outermost air on the jet is enhanced, thus the spray cone angle decreases. Experimental results show agreeably to the theoretical analysis, and the spray cone angle decreases from 19.7 degree to 11.5 degree when the air pressure drop increased from 0.63 MP to 1.55 MP.
Three cases of different recess sizes under the same working condition in the premise of tripropellant were investigated. The injection pressure drops of air, oxygen and alcohol are about 0.96MPa, 1.14MPa and 1.05MPa, respectively. Fig. 9 shows the spray field of the three cases. As shown in the Figure, the injector recess size affects the atomization performance. The longer the recess size, the larger the spray cone angle. However, the overall trend is not obvious.

![Figure 8. Spray field of bipropellant with different air pressure drop](image)

In order to study the effect of air circular seam size on spray cone angle, test on three groups of injector models were carried out. In the contrast experiment, air flow rate keeps constant, and the injection pressure of oxygen and alcohol are about 1.14MPa and 1.05MPa, respectively. To have a thorough analysis, the spray field of three cases are photographed in Fig. 10, which shows that on the premise of constant air flow rate, the spray cone angle gets larger with the increase of air circular seam size. Because in case of constant air flow rate, the increase of air circular seam size means the decrease of air injection pressure drop, which enlarge the spray cone angle, and the result is consistent with the conclusion above.

![Figure 9. Spray field of cases with different recess sizes](image)
3.3. Saunter mean diameter (SMD)

Injector particle diameter usually refers to the SMD (Saunter mean diameter) for CAH. Its physical meaning is the same size with the diameter of droplets instead of actual droplets, keeping the surface size 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. Meanwhile SMD research supplies reference for the design and improvement of injector, on the other hand, provides numerical simulation of CAH with a certain initial conditions.

Figure 11 shows the distribution of SMD in different distance cross-sections (measuring distance refers to the height from injector exit to the laser axis center) of Case00 under different injection pressure on the condition of bipropellant, in which the alcohol pressure drop was kept at about 0.99 MP, while the air injection pressure were set at 0.34Mpa, 0.77MPa and 0.96MPa. The result shows that SMD at the same cross-section increases with air pressure drop within a certain range, while the alcohol pressure drop remains unchanged. Because the atomization of gas-liquid coaxial flow injector was achieved by aerodynamic atomization and pressure atomization, and the former is dominant. When the alcohol pressure drop is constant and the air pressure drop increases, the shear action between the gas and liquid increases, which is beneficial to the liquid column breaking into the droplet, that is to say, primary atomization is better. At the same time, due to the increase of the air jet momentum, the droplets were enveloped to a certain extent, leading to the restriction on transverse movement of droplets, and the penetration will be reduced. In this case, the droplets were restricted in a small region, thus affecting the further interaction between the droplet and air, resulting in poor secondary atomization. Besides, when the measuring distance reaches to a certain value, which is to fully atomized, the SMD value tends to the same order of magnitude, and differs very little.

To obtain detail effects of injector structure size on atomization performance, the SMD of various cases were investigated. Figure 12 shows the SMD distribution of cases with different recess size under the same injection pressure drop. It can be seen from the figure, with the increase of recess size, the SMD increases first and then decreases. There exists an optimal recess size to obtain smaller SMD.
The SMD distribution of cases with different air circular seam size are shown in Figure 13, keeping the test condition constant (including air mass flow, the pressure drop of alcohol and oxygen). In agreement with conclusions in the previous paper, the increase of air circular seam size contributes to the atomization performance, namely, the SMD decreases with the increase of air circular seam size. Because in the premise of unchanged air mass flow, the increase of air circular seam size leads to the decrease of air injection pressure drop. According to the previous research, the decrease of the air injection pressure drop results in smaller SMD to some extent.

4. Conclusion
The sprays of gas-liquid coaxial flow injector with different recess sizes and air circular seam sizes were characterized with a Malvern optical instrument and Single Lens Reflex (SLR) camera. The effects of injection pressure drop, structure sizes on mass flow rate, spray field, spray cone angle and SMD were analyzed and discussed. The research is concluded as follows:
(1) The gas phase significantly improves the atomization effect, and increases the spray cone angle. However, as the injection pressure drop increases, the auxiliary function of outside air turns to be a form of envelop for the spray, thus decreasing the spray cone angle.

(2) Under the same test conditions, the recess sizes and air circular seam sizes have little influence on the spray cone angle.

(3) The SMD decreases with the development of the spray. Within a certain range, the SMD of the same cross-section increases with the gas injection pressure drop. Besides, with the increase of recess size, SMD increases first and then decreases.

(4) In case of constant air flow rate and the injection pressure drop of the other two elements, the SMD decreases with the increase of air circular seam size.

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