EXPERIMENTAL STUDY ON THE SPRAY CHARACTERISTICS OF INTERNAL-MIXING GAS-LIQUID INJECTOR UNDER AMBIENT PRESSURE

W. Qiao¹, B. Jia², X. Liu³, S. Wang⁴, L. Yang⁴, Q. Fu¹·⁴·*.
¹ School of Astronautics, Beihang University, Beijing 100191, China
² Institute of Combustion and Thermal Systems, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
³ Beijing Society of Thermophysics and Energy Engineering, Beijing, 100190, China
⁴ Ningbo Institute of Technology, Beihang University, Ningbo 315100, China

Abstract
To determine the spray characteristics of internal-mixing gas-liquid injector for various operating conditions under ambient pressure, the experimental facilities with backpressure chamber for spraying are established. By means of high-speed camera, Shadow Sizer system and POD method, the effects of gas-liquid momentum ratio, backpressure, pressure drop on the spray characteristics have been investigated in detail. Experimental results demonstrated that as the gas-liquid momentum ratio increases, the spray angle shows an overall increasing trend. The spray angle decreases with increasing backpressure. The spray penetration distance increases as the gas-liquid momentum ratio increases. The penetration distance increases slightly with increasing backpressure. The droplet size decreases and then increases with increasing backpressure. Furthermore, the increase of backpressure can inhibit the unstable oscillation of the spray.

Keywords: internal-mixing, gas-liquid injector, spray, ambient, backpressure

1 Introduction
Internal-mixing gas-liquid (IMGL) injector enhance the performance of liquid atomization and mixing through the interaction of gas-liquid two phases. It has the advantages of simple structure, large liquid supply, good atomization performance and other advantages. Internationally, many models of engines, such as liquid rocket engine, internal combustion engine and gas turbine engines have used the internal-mixing gas-liquid injector [1-3]. However, there is little research literature on the IMGL injector. It is of great significance to study the atomization mechanism and spray characteristics of this type injector.

Up to now, a number of scholars have attempted to study the spray characteristics of various types of injectors under ambient pressure conditions [4-9]. To investigate the spray under high backpressure similar to a real rocket engine, the most critical thing is to build a backpressure chamber. Kenny et al. [10] fabricated a back-pressure chamber that could reach 9.65 MPa. The spray experiments using a liquid swirl injector showed that increasement in the backpressure of the chamber increased the aver-age liquid film thickness of the injector and made the spray cone angle smaller when the mass flow rate was constant. Few researchers have studied the atomization process and spray characteristics of IMGL injector, especially under backpressure condition.

In this paper, spraying experimental facilities with backpressure chamber for an IMGL injector is built. High-speed camera, Shadow Sizer system, POD method and other means are used to study the spray characteristics under different backpressure conditions. The effects of gas-liquid momentum ratio, backpressure and pressure drop of gas feedline on the spray patterns, spray angle, penetration distance and droplet size distribution are investigated in detail. Finally, the inhibitory effect of backpressure on the spray oscillations is also analyzed by the POD method.

2 Experimental Methods
2.1 Experimental facilities
Figure 1 shows the spraying experimental setup for the internal-mixing gas-liquid (IMGL) injector under ambient pressure environment. This experimental bench can carry out spraying experiments under 0.1–4 MPa backpressure, and monitor and collect spray images, spray particle size, and feedline pressure. It
mainly includes a backpressure chamber system, a propellant supply system, an IMGL injector, an image acquisition system, a spray particle size measurement system and a pressure acquisition system. Water is used for the liquid simulant, and nitrogen is used for the gas simulant. The pressure in the backpressure chamber is high, and the pressure of the water tank to supply the liquid is low. This makes it difficult to supply liquid to the injector under high backpressure to achieve the specified flow rate. Therefore, the flow rate of the liquid feedline is supplied through a plunger pump. The flow rate of the liquid feedline is regulated and monitored by an electromagnetic flow meter whose opening can be adjusted.

As shown in Fig. 1, the nitrogen from the high-pressure liquid nitrogen tank is regulated through a capacitive gas flow controller and then supplied to the gas channel of the injector. The pressure in the backpressure chamber is supplied by another high-pressure nitrogen tank regulated by a pressure reducing valve. The liquid feedline, gas feedline and the exhaust pipe of the backpressure chamber are equipped with solenoid valves, which can operate the experiment remotely to ensure the safety of personnel. The pressure in the backpressure chamber, gas and liquid feedlines is monitored and collected by micro pressure sensors. The image acquisition system mainly consists of a high-speed camera, LED light source, and computer. The spray particle size measurement system uses the ShadowSizer shadow particle size measurement system. The backpressure chamber has glass windows in each of the four directions: front, back, left, and right. The backpressure chamber has four glass viewports in the front, back, left and right directions. The high-speed camera for image acquisition and the background light are placed opposite each other on both sides of the windows, while the long-distance microscope camera and the LED strobe light source of the particle size measurement system are placed opposite each other on both sides of the other pair of windows. The schematic of the IMGL injector is featured in Fig. 2. The gas-liquid injector here is an internally mixed gas-liquid direct-current injector.

**2.2 Experimental conditions**

Based on the actual structural dimensions and operating conditions of the IMGL injector during the hot test, the experiment scheme of 3 and 4 MPa backpressure was designed. To study the effect of the operating conditions on the spray characteristics more generally, dimensionless parameters need to be introduced. The gas-liquid momentum ratio (GLMR) is a key working condition parameter during the operation of a gas-liquid injector. For each operating condition in the experiments, the corresponding GLMR is calculated as shown in Table 1.
2.3 Experimental techniques

The spray patterns were captured instantaneously by a backlighting photography technique. The shutter time was set to 5 µs, and the instantaneous spray images with 1024 × 1024 pixels were obtained correspondingly. The frame rate was set to be 6400 frames/s as the best compromise for all experiments. The droplet size and its distribution of the spray field were measured by a Shadow Sizer system (Dantec Dynamics, Copenhagen, Denmark). The spray angle is defined as the angle between two tangents from the injector exit edge to the outer envelope of the spray cone. 50 images from the back-lighting photography were measured for each operating condition to obtain the average spray angle. The spray penetration distance is used here to describe the penetration depth of the spray field. For each operating condition, 50 images from the back-lighting photography were measured to obtain the average penetration distance. Proper orthogonal decomposition (POD) is an effective way to extract the information of each mode of experimental data. It can decompose a complex system into several simple orthogonal modes. In this study, the first two-order orthogonal modes of the spray field under backpressure are analyzed. The spectral feature information is extracted to explore the oscillation characteristics of the spray field.

3 Results and discussion

3.1 Spray patterns

Figure 3 shows the spray images for each condition when the injection pressure drop ΔP of gas feedline is gradually increased under different backpressure conditions, respectively. For each spray condition under backpressure, the spray field droplets gradually changed from sparse to a fog torch with a large droplet concentration with the gradual increase of the pressure drop ΔP. And the range of spray field distribution gradually expands with the increase of pressure drop ΔP. In addition, for the sprays under different backpressures at the same pressure drop, there is a slight decrease in the spray distribution range at higher backpressures. However, there is some increase in the penetration depth of the spray. The effect of backpressure on the spray angle and penetration distance will be quantitatively investigated in the following section.

3.2 Spray angle and penetration distance

As shown in Fig. 4, for various backpressure cases, the spray angle shows an increasing trend in general as the gas-liquid momentum ratio increases. Moreover, the higher the backpressure, the higher the rate of increase in spray angle with increasing gas-liquid momentum ratio. The greater the gas-liquid momentum ratio, the greater the inertial force of the gas relative to the liquid and the ambient stationary gas outside the injector. The larger gas momentum causes the broken liquid lumps and droplets to spread around downstream of the injector, resulting in a larger spray range, i.e., a larger spray angle.
Figure 4: Effects of gas-liquid momentum ratio (GLMR) on the spray angle

The effect of backpressure $P_b$ on the spray angle under different pressure drops is shown in Figure 5. It is obvious from the figure that the spray angle decreases with the increase of backpressure. That is, the ambient backpressure has a binding effect on the spray field, making its spray range smaller. The reason for this phenomenon is that when the backpressure of the spray environment increases, the gas density in the environment also increases significantly. At this point the inertia of the ambient gas at rest increases relative to the gas and liquid sprayed from the injector. That is, the resistance of the ambient gas to injection into the injector is increased. Therefore, the spray range is cut down and the spray angle becomes smaller. In addition, it is also analyzed that for a constant backpressure, the larger the gas injection pressure drop, the larger the spray angle.
Figure 5: Effects of backpressure $P_b$ on the spray angle

Figure 6 shows graphs of the effect of the gas-liquid momentum ratio (GLMR) on the spray penetration distance under different backpressure. For various cases of backpressure, the spray penetration distance obviously increases with the increase of the gas-liquid momentum ratio. The reason for this is because the gas impact downstream of the injector is greater when the gas-liquid momentum ratio is higher. This drives the liquid mass and droplets to flow further downstream, i.e., the penetration distance is greater. It is also observed from the figure that for higher backpressure, the penetration distance increases at a higher rate with increasing gas-liquid momentum ratio.

The graph of the effect of counterpressure $P_c$ on the spray penetration distance under different pressure drops is provided in Fig. 7. The spray penetration distance gradually increases with the increase of backpressure. That is, the backpressure is able to increase the spray penetration distance so that the spray acts farther away. This can still be explained by the effect of pressure on gas density. For a fixed injection pressure drop, the pressure in the gas feedline increases as the ambient backpressure increases. Therefore, the gas density also increases. In addition, from the figure, it is also analyzed that for a constant backpressure, the greater the gas injection pressure drop, the greater the spray penetration distance. This is due to the fact that the gas flow of gas feedline increases when the injection pressure drop increases. The gas and liquid momentum at the injector outlet are then increased, so it carries the droplets to be sprayed over a longer distance.

3.3 Distribution of spray droplet size

In Figure 8, the statistical distributions of spray droplet sizes at each backpressure are shown when the injection pressure drop $\Delta P$ is maintained at 2 MPa. When the backpressure is higher (3 MPa), the droplet size increases. The particle size is around 100 μm and occupies a large proportion of the weight. When the backpressure increases, the range of droplet size distribution also becomes wider. That is, the phenomenon of uneven droplet size is more obvious. The increase of backpressure will make the spray droplet size also increase, and exacerbate the inhomogeneity of the atomized droplet size. This is due to the fact that the increase in backpressure increases the density of the gases in the environment. This results in greater resistance to the droplet population moving downstream in the spray field.
Fig. 7: Effects of backpressure $P_b$ on the penetration distance.

Fig. 8: Spray droplet size distribution under different backpressure when $\Delta P=2$ MPa, $P_b=3$ MPa.

Fig. 9: Effects of gas-liquid momentum ratio (GLMR) on the characteristic diameter $D_{32}$. From the figure, it can be seen that as the gas-liquid momentum ratio (GLMR) increases, the overall trend of spray droplet size is decreasing. This can be explained by the fact that when the gas-liquid momentum ratio is larger, the aerodynamic force and shear effect of the gas on the liquid block and liquid filament are enhanced. This obviously promotes liquid fragmentation atomization. So the droplet diameter is smaller.

It can be seen from Fig. 10 that when maintaining a certain pressure drop in the gas feedline, the spray droplet size increases with increasing backpressure from the overall trend. In addition, it is also found that for a constant backpressure, the larger the gas injection pressure drop, the smaller the droplet size basically tends to be. This is due to the fact that the flow of gas feedline increases when the injection pressure drop increases, leading to an increase in the shear effect of the gas on the liquid phase. This helps the liquid phase to break up and atomize, so the droplet size decreases.
3.4 Modal analysis of the spray field

The dynamic sprays under each backpressure condition were processed for injector 1 and injector 2, respectively, when the injection pressure drop was maintained at 2 MPa. Their orthogonal modal decomposition diagrams corresponding to the spray at each backpressure were obtained, as shown in Fig. 11. The first two orders of modes for POD analysis are given for each backpressure condition since the lower order modes have higher energy. From the figures it can be seen that the modal decompositions...
of each injector under four backpressure conditions can reflect the oscillations of the "shoulder" at the periphery of the spray, except for the spurious signals caused by the disturbance of the airflow around the spray field. From the information of orthogonal mode decomposition, it can be seen that the first, second, third and fourth order orthogonal modes are alternately transformed symmetrically or asymmetrically next to each other. This reflects the oscillations on the left and right sides of the spray field.

4 Conclusions

In this paper, an experimental apparatus for spraying under backpressure was built. Using a high-speed camera and the Shadow Sizer system, spraying experiments were carried out on two scaling schemes of internally mixed gas-liquid injectors under backpressure environment. The spray patterns under different gas and liquid flow conditions were mainly analyzed. The effects of gas-liquid momentum ratio and backpressure on spray cone angle, penetration distance and droplet size were analyzed. Then, the unsteady oscillations of the spray field were analyzed by the POD method. As the gas-liquid momentum ratio increases, the spray angle shows an overall increasing trend. The spray angle decreases with increasing backpressure. The greater the gas injection pressure drop, the greater the spray angle. The spray penetration distance increases as the gas-liquid momentum ratio increases. The spray penetration distance increases slightly with increasing backpressure. The greater the gas injection pressure drop, the greater the spray penetration distance. As the gas-liquid momentum ratio increases, the overall spray droplet size tends to decrease. The droplet size decreases and then increases with increasing backpressure. For a given backpressure, the larger the gas injection pressure drop, the smaller the droplet size tends to be. With the increase of backpressure, the distribution range of wave belly and trough of the oscillations on both sides of the spray is wider, but the intensity of the oscillations is reduced, which indicates that the increase of backpressure can inhibit the unstable oscillations.

References