Study on cyclic variation rate of fuel flow in the nozzle during fuel injection

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Abstract
The fuel flow pattern in the fuel injection nozzle of diesel engine is a complex and changeable phenomenon, which is easily affected by various factors, bringing the differences of flow patterns between multiple injection cycles. To solve the above problem, a visual experimental platform of fuel injection nozzle was built, in which the 100 injection cycles of diesel engine on the same working condition were photographed via shadowgraphy to study the difference in fuel flow pattern in the nozzle by ensemble average processing method. The cyclic variation rate $K$ of fuel flow pattern is defined. Results demonstrate that the fuel flow pattern tends to be the same in multiple fuel injection cycles, but there is a strong randomness at the starting of injection and after ending of injection; the $K$ can be reduced by decreasing the injection pressure and the inclination angle of orifice, so that the fuel flow pattern in the nozzle tends to be consistent.

Keywords
Engine, nozzle, ensemble average processing, fuel flow pattern, cyclic variation rate

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Introduction
The atomization quality of fuel in engine combustion chamber directly affects combustion quality, thus affecting fuel economy and emission of engine. The fuel flow state in the nozzle has an important impact on fuel atomization, and many scholars and researchers have conducted in-depth researches on the fuel flow state in the nozzle.

In terms of experimental methods, as early as 2005, Takenaka et al. used neutron radiography to photograph the fuel flow in the metal injector and processed the experimental pictures by the ensemble average processing method. Subsequently, X-ray imaging and neutron imaging were widely used in the study of fuel flow in the nozzle. Ghiji et al. used laser backlight imaging technology to analyze the spray structure. Due to the influence of aerodynamics, the mushroom head shape appeared at the front end of the jet, and the shock wave phenomenon was captured by Schlieren method in the jet atomization area. However, for most researchers, it is still an acceptable option to use transparent materials to make a visual transparent nozzle to study fuel cavitation. When processing a transparent nozzle, the actual size of the nozzle is extremely small, which makes it difficult to be manufactured, and it is more difficult to capture a clear fuel flow image with a real-size nozzle. Therefore, based on the principle of similarity, some scholars conducted experimental research on the scaled transparent nozzle under the premise of ensuring the geometric similarity between the experimental nozzle and the real-size nozzle. However, in order to obtain more reliable and convincing test results, it is still a better option to use a real-size transparent nozzle to study the fuel flow state.

There are many types of fuel cavitation, which can be simply divided into sac hole cavitation and orifice cavitation according to the location in the nozzle. The former mainly occurs when the needle valve is lifted/seated. The drastic changes in fuel pressure and flow rate cause the pressure in the sac hole to decrease. When the pressure is lower than the saturated vapor pressure of the fuel, it will cause cavitation in the sac hole. The orifice cavitation is caused by the shrinkage of the flow area when the fuel enters the orifice from the sac hole, which causes the flow rate to increase and the pressure to...
decrease. According to the cavitation form, the cavitation in the orifice can be roughly divided into film cavitation, cloud cavitation and string cavitation.\(^\text{17}\) According to the flow characteristics of fuel in the nozzle,\(^\text{18}\) it can be divided into five different flow states: turbulence, primary cavitation, super-cavitation, ejection flow and local readhesion flow.

Cavitation in the nozzle is easily affected by various factors. Jiang et al.\(^\text{19}\) studied the effect of different fuels on cavitation in the orifice. Results showed that the viscosity of fuel and the saturated vapor pressure would affect the inception time and strength of cavitation. At the same time, there would be residual ingestion bubbles in the nozzle after EOI (end of injection), and the bubble size was affected by the nozzle diameter and fuel surface tension.

Pressure is another vital factor affecting cavitation. Qiu et al.\(^\text{20}\) pointed out that the cavitation in the nozzle would be obviously enhanced with the increase in injection pressure or decrease in back pressure. Besides, some scholars and researchers have pointed out that there is a special cavitation phenomenon called string cavitation in the process of fuel injection,\(^\text{21,22}\) which would lead to different fuel flow patterns in different injection cycles under the same working conditions, and then lead to different fuel atomization quality under different cycles.

Because the fuel flow state in the injector is complex and changeable, some researchers began to be interested in the difference of the fuel flow state in multi-cycles. In 2013, Mitroglou and Gavaises\(^\text{23}\) conducted the experiment again using enlarged size fuel injectors and processed the results by the ensemble average method. The result revealed the significant influence of the sac hole volume and needle valve lift on the fuel cavitation. And then, Mitroglou et al.\(^\text{5}\) took plenty of experiments using a real-size fuel injector with six micro-channel orifices, and the ensemble average images showed that the fuel cavitation distribution in the orifice presented a significant cyclic variation, which affected the fuel spray distribution at the orifice exit. Ma et al.\(^\text{24}\) also processed the experimental images by ensemble average method. Results showed that the cavitation amount in the nozzle would increase with the decrease in needle valve lift or the increase in injection pressure. In addition, the author pointed out that the cavitation phenomena would change in cycles.

From the previous studies on cavitation in the fuel injector, it can be known that there are many factors affecting the cavitation in the fuel injector during injection, and it exhibits strong randomness in temporal and spatial characteristics. The fuel flow in the injector is the upstream boundary of fuel atomization, and the randomness of cavitation will affect the atomization and combustion of fuel. Therefore, to explore the influence of different factors on the cyclic variation rate of fuel flow, in this paper, the cyclic variation rate of fuel flow pattern in the injection cycles under different conditions is analyzed.

**Experimental setup and method**

**Experimental setup**

As shown in Figure 1, the experimental setup consists of two parts: high-pressure common-rail fuel injection system (high-pressure oil pump, common-rail pipe, synchronizer and electromagnetic fuel injector) and image acquisition system (high-speed framing camera with long focal distance microscope and light supplement system).

The high-pressure common-rail system is Delphi Multec DCR1400 (Taian, China), equipped with a pressure sensor on a common-rail pipe for feedback control of rail pressure. The fuel injection system is driven by DB2000-75 oil pump test bench (Taian, China). And a control application named Visu98 was applied to control the injection pressure and the fuel injection quantity. The high-speed framing camera system includes the VEO-7101 camera which was produced by York Company of the United States. The camera has 36 GB of memory, a maximum shooting rate of 70,000 frames per second, and is controlled by the Phantom Camera Controller application. The micro magnifying lens is QUESTAR QM100, which can magnify the object up to 381 times, the resolution is 1.1 μm, the working distance is between 15 and 35 cm and the field of view diameter is between 0.375 and 8.0 mm. Then, the light supplement system used LED light source (SuperFire L1, China), whose power is 50 W.

In this experiment, due to the limitation of the experimental setup and to avoid damage to the transparent injector, the rotational speed was set at 250 rpm, and the main injection flow rate was 10 mg/s. Besides, the injection pressure was 30 MPa and the back pressure was equal to atmospheric pressure, which means the fuel could be injected into a free atmosphere directly. And then, the shooting frequency of high-speed framing camera was set as 20,000 fps, which meant that the interval between two images is 50 μs. In order to effectively freeze the flow field, the exposure time was set as 1 μs, and the shooting pixel was set as 512 × 600 pixel\(^2\). Under this shooting condition, the longest time for each shooting is 4 s, about 17 injection cycles. And then, it takes about 15–20 min to save the data. Therefore, the influence of thermal effects on the results can be ignored.

The optical transparent nozzle is the key component to achieve a high-quality flow image inside the nozzle. In this paper, the transparent nozzle with an oblique cylindrical orifice is made by polymethyl methacrylate (PMMA). It has an excellent light transmittance, and its refractive index (\(n_{\text{PMMA}} \approx 1.49\)) is close to that of diesel (\(n_{\text{diesel}} = 1.46–1.51\)),\(^\text{25}\) which can eliminate the influence of transparent materials on imaging. The transparent nozzle required for this experiment is processed by machining method, and the basic dimensions of the transparent nozzle are shown in Table 1 and Figure 2 shows the
sketch of nozzle A. After trying to process the injection holes with the aperture of 0.1 mm and 0.2 mm, it is found that the small aperture increases the difficulty of processing, and at the same time, the error is large in the processing process, which eventually leads to the rough inner wall surface and difficulty in ensuring the precise size of the aperture. These problems may have a great impact on the experimental results. Therefore, the final selection is easier to process and smaller error of 0.3 mm aperture.

The fuel injector is a Delphi electromagnetic injector, whose ball part is moved, as shown in Figure 3(a), and the transparent nozzle is shown in Figure 3(b). Then the transparent nozzle and the injector are bonded with epoxy resin adhesive to form a transparent nozzle for the experiment, as shown in Figure 3(c). All tests used the same fuel injector but replace the transparent nozzle.

The experimental methodology in this paper is the shadow imaging method. Because the transparent nozzle is made by PMMA material, whose refractive index is almost the same as that of diesel, so light can go through the diesel and the nozzle in a straight line without refraction. However, due to the existence of cavitation, light will be refractive, resulting in a darker cavitation area and a brighter fuel area in the nozzle, as shown in Figure 4(a).

**Image processing**

Because of the test images taken by the high-speed framing camera are only black and white, it is difficult to distinguish the cavitation intensity in the nozzle directly by naked eyes, as shown in Figure 4(a). Therefore, the image ensemble average processing method is adopted. This method is to calculate the test images simultaneously under multiple fuel injection cycles to obtain the mean image at that time. It is necessary to convert RGB image into gray image before ensemble processing, and then to obtain the mean image, as shown in equation (1) and (2).

\[
H_i = R_i \times 0.3 + G_i \times 0.59 + B_i \times 0.11 \quad (1)
\]

\[
\overline{H_i} = \frac{\sum_{i=1}^{n} H_i}{N} \quad (2)
\]

\(R_i, G_i, B_i\) represent the red, green and blue values of pixel \(i\), respectively, \(n\) represents the total number of pixels in the image, and \(H_i\) represents the gray value of pixel \(i\) in the image, ranging from 0 to 255. \(N\) is the total number of pixels in the image.
image samples, which is equal to 100, $\bar{H}_i$ is the average gray value of pixel $i$ after ensemble average processing, and the range is 0–255.

The significance of gray processing of the test images is that the cavitation intensity which is difficult to distinguish by naked eye can be converted into gray value. Due to the imaging principle of shadow method, the more serious the cavitation is, the lower the brightness of the region is, and the smaller the gray value of gray image is. When the gray value is 0, it indicates that the region has been completely cavitation. Furthermore, the background of the images remained the same throughout the test, so the gray-scale value of the background did not change. Therefore, subtracting the background image of the test from all the test images can avoid the systematic error in the test process.

After the ensemble average processing, the experimental image was pseudo colored according to the gray value, as shown in Figure 4(b). Compared with Figure 4(a), it can be seen obviously that the fuel area with higher brightness turns bright yellow, while the cavitation area close to black turns blue. The picture contrast is stronger, which makes the color change in black area which cannot be distinguished by naked eye also has a more intuitive performance in image. It can be seen that the blue area changes from light blue to dark blue, reflecting the spatial distribution of the cavitation area. The deeper the blue is, the stronger the cavitation intensity is.

Besides, to study the difference of experimental phenomena under different cycles, the standard deviation of gray value of each pixel in the images under all cycles is calculated, and the coefficient $K$ is defined to represent the change rate at a certain time under multiple cycles. The smaller the $K$ is, the more consistent and repeatable the experimental phenomena is. On the contrary, the larger the $K$ is, the greater the difference and randomness of the experimental phenomena are. The calculation method of $K$ is shown as equation (3).

\[
K_n = \left( \frac{1}{N} \sum_{i=1}^{n} S_i \right) / \left( \frac{1}{N} \sum_{i=1}^{n} \bar{H}_i \right) \times 100\%\quad (3)
\]
In equation (3), $S_i$ represents the standard deviation of gray value at pixel $i$, $n$ is the total number of pixels in the image and $K_n$ represents the nozzle cyclic variation rate. In the same way, $K_s$ and $K_o$ are defined into the cyclic variation rate in the sac hole and orifice, respectively, in this paper.

**Selection of test times**

Due to the possible test error, the $K$ value under different fuel injection cycles is analyzed to select the reasonable test times. Figure 5 shows the change curve of $K_n$ at the injection time $t = 0.50$ ms when the injection cycle times are 30, 50, 80, 100, 120 and 140, respectively. It can be seen from Figure 5 that when the number of injection cycles is increased from 80 to 100, $K_n$ increases 3.2%. However, the $K_n$ only increases by 1.4% when the number of injection cycles is increased from 120 to 140. This demonstrates that when the times of injection cycle is small, due to the randomness of cavitation phenomenon, and the shape and spatial distribution of fuel cavitation are greatly different, which leads to the increase in fuel injector $K_n$ value, and gradually decreases with the increase in cycle times. This indicates that cavitation begins to show some regularity at this time. Therefore, for reducing the workload of the test and obtaining reasonable test data, this paper selects 100 test times of fuel injection to analyze the results.

**Result and discussion**

**Law of needle valve movement**

Figure 6 shows the law of injector needle valve movement under three injection pressures when the injection flux is 10 mg/str. When the needle valve position is above half of the highest point, it is defined as the stable injection period. It can be seen from Figure 6 that when the injection pressure is 30 MPa, 0–0.3 ms is SOI (start of ingestion), 0.3–0.65 ms is stable injection period and 0.65–0.9 ms is EOI. Then, similar time segments can also be obtained for the curves at 40 MPa and 50 MPa according to the same division standard.

**Fuel flow pattern in the nozzle**

The fuel injection pressure is 30 MPa, and the nozzle for the experiment is nozzle A, whose dimension parameters are shown in Table 1. Figure 7(a) shows the growth process of cavitation and ingestion in the nozzle, and Figure 7(b) shows the images after ensemble average processing. In the SOI, from 0 to 0.15 ms, there are stagnant bubbles in the sac hole and in the orifice from last injection. The stagnant bubbles may come from a small amount of fuel vapor, or from air from a previous injection, and it can be observed that the bubbles in the orifice have a slight backflow phenomenon with the fuel. The reason for this phenomenon is that the needle valve is lifted upward, but the fuel does not flow into the sac hole at this time. As the needle valve continues to lift up, the fuel enters the sac hole through the sealing surface, which makes the pressure in the sac hole increase rapidly, and the volume of the bubble is compressed and, eventually discharged out from the orifice. These bubbles have an important effect on the initial break up, the difference in the position and quantity of the air bubbles will result in different shapes of the fuel spray tip, and the corresponding spray characteristics (penetration distance, spray cone angle) are also different.

The period of stable fuel injection is from 0.3 to 0.6 ms, and severe cavitation phenomenon and obvious wall-attached flow phenomenon can be seen in the orifice during the time. The cavitation in the orifice is mainly caused by the throttling effect. When the fuel flows from

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**Figure 5.** $K_n$ at different injection cycles.

**Figure 6.** Law of needle valve movement under difference injection pressures.
the sac hole into the orifice, the circulation area suddenly shrinks. From the continuity equation and Bernoulli equation, it can be seen that the fuel flow rate in the orifice increases and the pressure decreases. When the ambient pressure in the orifice drops to the saturated vapor pressure at this temperature, the fuel will undergo a phase change to produce cavitation bubbles, which means the cavitation inception. As the injection process progresses, cavitation in the orifice continues to develop, and finally, super-cavitation is formed, that is, cavitation bubbles penetrate the entire orifice.\textsuperscript{28} As shown at 0.3 ms.

When the fuel injection period comes to the EOI (0.7 ms), the cavitation phenomenon in the orifice is consistent with the stable injection period, and there is no cavitation bubble in the sac hole. Then, the cavitation occurs in the sac hole (0.75 ms) while the needle valve is about to be fully seated, and the cavitation location is at the sealing surface. The cavitation is caused by the stretching of the fuel from the orifice to the sac hole, and there are the most serious fuel streamline shrinkage and the strongest stretching effect at the contact position between the sac hole and the needle valve, so the cavitation inception of

![Flow image in the nozzle at different time.](image-url)

*Figure 7. Flow image in the nozzle at different time.*
the sac hole appears here. Collapse of cavitation bubbles in the orifice is the reason for air ingestion. At 0.80 ms, the ingestion of external air and the collapse of cavitation bubble almost occur at the same time, or a part of air has backflowed into the orifice when cavitation occurs. At 0.9 ms, the vapor bubbles in the orifice have completely collapsed, and the external air flows backward to the nozzle to form a complete gas column. At the same time, it can be seen that the ingestion bubbles in the orifice flow back into the sac hole and form a huge bubble. The cavitation at the sealing surface of the sac hole disappears, indicating that the cavitation in the sac hole has also collapsed at this time. Meanwhile, the external gas begins to flow back into the sac hole and gradually diffuses to other parts (1.00 ms, 1.20 ms).

Comparing the experimental images of a single cycle with the mean images, it can be found that the overall trend of fuel flow pattern is generally consistent, especially in the stable injection period and the initial stage of needle valve seating (0.3–0.7 ms). Figure 7(a) and (b) is basically the same, while the two images show that the initial stage of fuel injection (0.02–0.15 ms) and after EOI (0.75–1.20 ms), respectively, are different, which is mainly reflected in the spatial distribution of bubbles. It can be seen from Figure 7(a) that the bubbles in the orifice at the SOI and after EOI are not continuous, but composed of bubbles of different sizes. However, in Figure 7(b), it can be seen that the bubbles in the orifice exist in the form of continuous gas column and fill the orifice. The phenomenon in the sac hole is similar to that in the orifice, and the mean images can show the distribution location of bubbles well but not the geometry shape of bubbles.

The comparison between the random single cycle images and mean images shows that the fuel flow pattern in the nozzle is basically the same during stable injection in multiple injection times, and the experimental phenomena have good repeatability. At the SOI and after EOI, the spatial distribution of bubbles in the nozzle is roughly the same, but there is a big difference in the morphology and characteristics of bubbles. The strong randomness may be the key factor that causes the different atomization quality of each fuel injection.

**Analysis of K of experimental results**

Figure 8 shows the standard deviation of pixels in the picture at different injection times. It can be seen from the figure that the standard deviation in the orifice is smaller under different injection cycles, but after EOI (0.75 ms), the cavitation shape and location in the sac hole are different. On the whole, the overall standard deviation of Figure 8(a) to (g) is less than 30, while the standard deviation of some areas in the sac hole from Figure 8(h) to (l) is relatively larger. Compared with Figure 8, it can be seen that the fuel morphology in the nozzle after EOI will be greatly different from that before EOI. This difference is mainly reflected in the morphology of cavitation gas and ingestion bubble in the sac hole, but the spatial distribution changes are small, which means the location of the bubble in the sac hole is relatively fixed.

Figure 9 shows the variation curves of K of the nozzle at different parts of the nozzle and different injection times. It can be seen from the image that in the whole fuel injection cycle, K always keeps at a low value, less than 6%. But at the SOI and after EOI, K and K fluctuate greatly in the injection cycles, indicating that there is a certain degree of randomness in the shape of cavitation and ingestion bubbles in the sac hole at the SOI and after EOI. This may be caused by two reasons, one is the influence of needle valve movement on the turbulence intensity of fuel in the sac hole, which makes the turbulence intensity increase at the time when the needle valve is lifted and completely seated. And the randomness of turbulence also causes the different shapes of cavitation bubbles and ingestion bubbles in sac hole, too. The second reason is that the frame rate of the high-speed framing camera used in the experiment is set at 20,000 fps, which makes that the

![Figure 8](image-url)
injection time corresponding to the image cannot be exactly consistent, resulting in a bit experimental error. The $K$ of the whole injection cycle is always at a low level during the stable injection period and changes sharply before and after. From 0.15 to 0.30 ms, $K_s$ decreases by 59.9%, and $K_n$ and $K_o$ decrease by 43.3% and 30.2%, respectively; from 0.70 to 0.75 ms, $K_s$ and $K_n$ increase by 97.5% and 44.3%, respectively, while $K_o$ only increases by 3.2%. In the stable injection period, $K_s$ also decreases with the increase in injection time, from 5.3% of 0.3 ms to 4.1% of 0.6 ms, while $K_n$ and $K_o$ remain at about 4%. Referring to Figure 7, it can be seen that there is no cavitation in the sac hole at this time, and the fuel exists in the liquid phase. This indicates that the flow pattern of fuel in the nozzle is basically the same during the stable injection period, and the change in variation rate in the nozzle mainly comes from the orifice. Meanwhile, the above data also show that under the structure of the nozzle in this paper, the shape and spatial distribution of cavitation in the orifice are basically consistent during the whole injection period. However, the cyclic variation rate in the sac hole around EOI still increased significantly, indicating that cavitation phenomena should change more.

**Effect of injection pressure on $K$**

In order to study the influence of different injection pressure $P_i$ on injection cycle-to-cycle variation rate $K$, the experiment was conducted again under the condition of only changing the experimental injection pressure. Figure 10 shows the change curve of $K_n$ at different injection times when $P_i$ is equal to 30, 40 and 50 MPa, respectively. As shown in Figure 10, when $P_i=40$ MPa, $t=0.30$–0.60 ms, the $K_n$ is basically consistent with that of 30 MPa, while $K_n$ increases slightly in the range of $t>0.30$ ms and $t<0.60$ ms. When $P_i=50$ MPa, compared with 30 MPa, $K_n$ increases greatly, and when $t=0.15, 0.40$ and 1.2 ms, $K_n$ increases by 47.3%, 39.6% and 29.0%, respectively. In addition, it can be seen from Figure 10 that when injection time is in the range of 0.02–0.50 ms, the change trend of $K_n$ under the three injection pressures is consistent. When $P_i$ is equal to 50 MPa, $K_n$ increases rapidly between 0.50 and 0.60 ms, and while for 30 and 40 MPa, $K_n$ increases rapidly between 0.60 and 0.70 ms.

As shown in Figure 6, the reason for the above phenomenon is that when the injection pressure increases, the duration of injection is shortened and the movement law of needle valve changes, leading to an earlier sitting time. When $P_i=50$ MPa (Figure 11(c)), the needle valve is completely seated at 0.6 ms, and cavitation occurs in the sac hole at 0.65 ms, and when $P_i=30$ MPa (Figure 11(a)), the time for the needle valve to be completely seated and cavitation to occur is 0.7 and 0.75 ms. The time when the needle valve is completely seated and cavitation occurs is advanced, which leads to the rapid increase in $K_n$ at 50 MPa. At the same time, it can be seen from Figure 11(b) that there are micro cavitation bubbles in the sac hole when $t=0.70$ ms, which also explains the reason why the increase in $K_n$ is greater than 30 MPa between 0.6 and 0.70 ms when $P_i$ is equal to 40 MPa.

“Law of needle valve movement” shows the law of needle valve movement, which was also pointed out in the literature. He et al.\textsuperscript{31} reported that the movement of needle valve is different under different injection pressures, which can also be used to explain the reason why $K_n$ increases greatly when $P_i=50$ MPa. The greater the injection pressure is, the faster the needle valve moves. As mentioned in “Fuel flow pattern in the nozzle”, with the increase in needle valve movement speed, the disturbance in the

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**Figure 9.** Change in $K$ at different injection time.

**Figure 10.** Variation curve of $K_n$ at different injection pressure.
nozzle is intensified and the turbulence intensity of fuel also increases accordingly, which will lead to the increase in cyclic variation rate $K_n$. On the other hand, the fuel has a faster flow rate at high injection pressure, which also increases the disturbance in the nozzle, resulting in the increase in $K_n$.

**Influence of orifice angle on $K$**

Figure 12 shows the change curves of $K_n$ for the three kinds of the nozzles with different orifice inclination angles. The parameters of nozzle B and nozzle C are shown in Table 1. The injection pressure is 30 MPa.

It can be seen from Figure 12 that the value of $K_n$ gradually increases with the increase in inclination angle. Compared with Figure 12 and 9, it can be seen that the $K_n$ and $K_o$ are close to each other in the stable injection stage and is at the minimum value during the whole injection cycles. In Figure 12, even in the stable injection stage, the increase in $K_n$ is still very obvious with the increase in...
orifice angle. When the injection time $t = 0.5\, \text{ms}$, the $K_n$ of nozzle B decreases by $36.1\%$ compared with that of nozzle A, and that of nozzle C increases by $155.8\%$ compared with that of nozzle A, which indicates the orifice inclination angle has a significant effect on the fuel flow pattern in the nozzle. The reason for this phenomenon is that the corner at the entrance of the orifice increases with the increase in the orifice inclination angle, which enhances the fuel disturbance in the orifice, thus increasing the cycle-to-cycle variation rate of the fuel flow pattern. On the other hand, the single inclined orifice structure is adopted in the experimental nozzle, the asymmetric structure aggravates the fuel disturbance in the nozzle with a large orifice angle and further increases the $K$ in the nozzle.

**Conclusion**

1. The visualization test platform is built, through which the fuel cavitation shape and distribution area in the conical sac hole nozzle with a single inclined orifice can be observed completely and clearly. By comparing the images of single injection cycle and ensemble average processing, it can be seen that the shape of cavitation bubbles in the nozzle is different under different cycles, but the spatial distribution area is fixed: during the stable injection period, cavitation only occurs in the orifice, and mainly at the side of the larger corner of the orifice inlet; cavitation begins to appear in the sac hole before and after EOI, mainly distributes above the sac hole and keeps away from the orifice inlet.

2. The study of the standard deviation of experimental images and the cyclic change rate $K$ show that under different injection cycles, the change in fuel flow pattern in the orifice is very small at the same time. During the stable injection period, the $K$ in the sac hole is the same as it in the orifice, but at the SOI and after EOI, the $K$ increases rapidly, which indicates that the morphology of cavitation and ingestion bubbles in the sac hole are quite different at these periods.

3. The increase in the orifice inclination angle and the injection pressure can lead to the increase in the cyclic variation rate of the nozzle, but the change trend of $K$ remains unchanged. This is mainly because the increase in the injection pressure and the inclination angle enhances the disturbance in the nozzle, thus the fuel cyclic variation rate is improved. Therefore, for reducing the difference of cavitation phenomena in the nozzle, measures such as reducing the injection pressure and adopting a smaller orifice inclination angle can be adopted.

4. The ensemble average proceeding of multiple injection cycles, it is beneficial to study the influence of different nozzle structures of injection conditions on the cavitation morphology and distribution area in the injector. The research results are helpful for the further study of cavitation phenomenon in the nozzle and the design of the nozzle to get better fuel atomization quality of engine.

**Declaration of Conflicting Interests**

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