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Investigation of inner flow and near-field spray patterns of the non-circular diesel injector

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Abstract. The non-circular diesel nozzles have influence on the inner cavitation and near-field spray patterns. For this investigation, two different non-circular diesel injectors with the same equivalent diameter were adopted. A detailed comparison of near-field spray and inner cavitation behaviors were investigated by using near-field spray experimental visualization method and numerical model. The elliptical nozzle has larger discharge coefficient, indicating that using the elliptical nozzle could increase the circulation ability. Also, the elliptical nozzle outlet has higher vorticity magnitude at all injection conditions than those of the circular nozzle. Besides, the cavitation is evenly distributed in the circular orifice inner wall. While for elliptical nozzle, the cavitation is mainly distributed along the major axis. Moreover, the near-field spray cone angle and projection area at the major axis of the elliptical nozzle are all wider than the circular nozzle. Because the nozzle exit turbulence vorticity and the cavitation along the major axis direction are both more intense than the circular nozzle, and these factors could increase the diffusion of the initial spray. Finally, it is possible to predict that the atomization quality of the elliptical spray is better than that of the circular spray from the larger spray cone angle and projected area of the near-field elliptical spray.

Keywords. Diesel nozzle; cavitation; vorticity; near-field spray; spray cone angle.

1. Introduction

The fuel and air mixture quality depends on the fuel spray and atomization quality, which has an important influence on the emission of soot and nitrogen oxides for diesel engine [1–4]. The diesel nozzle has become one of the most critical components of fuel injection system, and several studies show that nozzle geometry can affect the internal cavitation flow and spray behaviors [5–7]. Especially, the non-circular diesel nozzle resulted in higher discharge coefficient and better fuel–air mixing quality, which is beneficial for reducing the engine emissions [8, 9]. Therefore, the geometry of diesel nozzle catches the attention of researchers.

Salvador *et al* [10] carried out numerical investigations on the inner cavitation of different convergent–divergent orifices and found that the higher convergence–divergence level orifice is helpful to increase the mass flow rate, and also larger convergence–divergence level orifice is easy to cavitate. Macián [11] studied the influences of cylindrical and convergent nozzles and injection pressures on the internal flow characteristics through simulation method and concluded that there was no cavitation in convergent nozzle. Payri *et al* [12, 13] investigated the cavitation flow and sprays patterns for different geometrical orifices. They demonstrated that smaller inlet rounding and conicity orifice is easier to cavitate, and also the values of spray cone angle for conical nozzle are smaller than that of the cylindrical nozzle. On the other hand, for the non-circular orifice with the elliptical cross section shape, Molina *et al* [14] numerical studied the influences of elliptical diesel nozzle with various aspect ratios and positions on the orifices flow patterns and inner cavitation behaviors. They found that the horizontally oriented elliptical nozzle has larger discharge coefficient. Hong *et al* [15] investigated the cavitation in the elliptical nozzle with the application of an larger transparent injector with different cross section shapes, the results show that the cavitation distribution along the major axis is longer than that of the minor axis. Yu *et al* [16] studied the effects of inner flow patterns on the downstream spray behaviors with the application of an elliptical gasoline direct injection injector, the results indicated that the turbulent vorticity at the nozzle exit is helpful to increase the spray breakup progress. Yu *et al* [17] also stated that the vorticity magnitude at the elliptical orifice exit is always higher than that of the circular orifice, and the results indicated that the using of elliptical nozzle is helpful to enhance the nozzle exit turbulence intensity.

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Furthermore, many experts and scholars have carried out a lot of researches on the near-field spray breakup characteristics with the application of different geometrical nozzles. Payri *et al* [18–20] performed a lot of research works on the effect of nozzle geometry on the spray characteristics through experimental and simulation methods and found that the conical nozzle holds longer spray liquid length, while the differences between conical nozzle and cylindrical nozzle are reduced at high injection pressure, and also found that nozzle exit velocity increases as the cavitation incepted in nozzle, because the cavitation adheres to the inner wall of the orifice to reduce the actual flow area of the orifice. He *et al* [21] investigated the effect of the orifice geometry on the inner cavitation and primary spray behaviors through experimental method. The results indicate that the divergent nozzle is easier to cavitate than the cylindrical nozzle, and the shedding cavitation bubble collapse at the nozzle outlet can increase the near-field spray cone angle. On the other hand, for the non-circular orifice injector, Yu *et al* [22, 23] compared the downstream spray characteristics with application of different cross section shapes orifices under the room temperature, the results showed that using an elliptical nozzle can reduce the spray tip penetration. While the elliptical spray has larger cone angle and the projection area compared to circular nozzle, indicating a better air-fuel mixing quality for the elliptical spray. Hong *et al* [24] also performed the visualization experiment on the cavitation flow and its effects on the initial spray behaviors with an enlarged transparent injector under the lower injection conditions, they reported that the inception of cavitation could increase the cone angle.

The aforementioned research works give a lot of important information for the influences of orifice geometries on inner cavitation, initial and downstream spray patterns. However, the discrepancies in the initial spray characteristics are due to the differences in non-circular cross section shapes of diesel injectors, or are in part because of the inner cavitation flow are still unclear. More importantly, when the non-circular diesel nozzle was employed, the non-axisymmetric cavitation distributions and its effects on the near-field spray morphology for non-circular diesel injector have not been investigated yet. Hence, considering the inner flow and near-field spray patterns have important effects on the downstream fuel atomization and fuel-air mixture formation. It is of great importance to carry out a deeper insight comparison of the near-field spray characteristics for the non-circular cross section shapes diesel nozzle particularly combining with the orifice exit and inner flow behaviors.

Therefore, in this paper, we investigate the effects of non-circular cross section shapes of diesel nozzle on the near-field spray combining with inner cavitation. The diesel spray images in the near-field of nozzle were captured by spray visualization system with a long-distance microscope, and the study of the inner cavitation patterns are also carried out through numerical methods imultaneously. Firstly, for the simualtion part, the difference of cavitation distribution between the circular and elliptical nozzles are deeply compared and analyzed, as well as the orifice exit flow parameters. Secondly, for the experiment part, the morphology near-field spray images for different cross section shapes orifices nozzles were captured by using a long-distance microscope at different injection pressures (100 MPa, 120 MPa) and the ambient condition is the atmospheric environment. Also, the near-field spray parameters for circular and elliptical diesel nozzles were compared and investigated combing with the nozzle inner flow behaviors.

2. Methodology

2.1 *Description of simulation approach*

It is difficult to process transparent non-circular holes, which poses challenges for the experimental study of the non-circular hole inner cavitation flow. However, with the improvement of the simulation method, the cavitation inception inside the orifice could be simulated accurately and more important information and parameters could be obtained for analyzing the mechanism of cavitation inception. Therefore, the computational method was used in the first part of the present research work. For the turbulence model, considering the Large Eddy Simulation (LES) model has the ability to get more detailed flow information as compared to the Reynolds-averaged Navier–Stokes (RANS) model [25], the LES turbulence model was used in this work. Besides, the cavitation model is Schnerr and Sauer model [26], it is believed that there are two phases in the nozzle orifice, one is the diesel liquid phase and another is the diesel vapor phase. Also, the detailed description and validation of the cavitation and turbulence models were presented in our previous works [27–29].

2.2 *Geometry and boundary conditions*

Cavitation inside the nozzle flow model includes the geometric model of creation and the division of mesh. For the mesh process, the mesh inside the orifice was encrypted. This paper mainly studied the flow inside the different cross section shapes nozzles and the near-field spray characteristics, therefore, we take the single-hole nozzle as the research object, and keep the orifice exit area under the same conditions. The diesel nozzles and the detailed mesh are shown in figure 1. Table 1 demonstrates the geometrical parameters for different cross section shapes nozzles, it reveals that the elliptical nozzle has larger perimeter and aspect ratio. Moreover, the nozzle exit areas for different

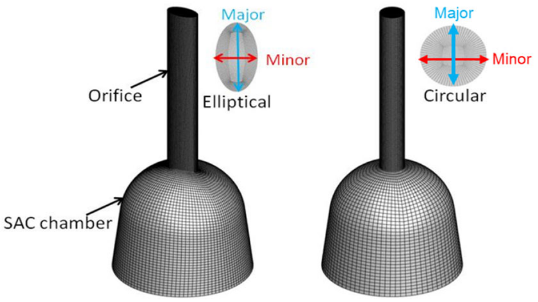


Figure 1. The geometrical models with different cross section shapes, elliptical and circular.

cross section shapes are kept the same and the equivalent diameter is 160 µm, and more detailed geometrical parameters are shown in table 1.

3. Near-field spray visualization text

3.1 *Experimental setup and test method*

The near-field spray characteristic experiment was carried out in a small constant volume vessel. The diesel injector was installed on the top of the vessel. The vessel was connected with the atmospheric environment and the bulk temperature was the ambient room temperature. The near-field spray test platform was shown in figure 2. A microscope (Navitar ZOOM 6000/12X) was installed in front of the high speed CCD (Charge-Coupled Device) camera to capture the near-field spray pattern, especially the lenses was adjusted to line up the center of the sensor in the high speed CCD camera with the center of the optical zoom. Therefore, the spray morphology of the 2 mm downstream of nozzle tip can be taken by CCD camera. The exposure time of the camera is fixed as 11 µs. The frame rate was set to 80,000 fps with a fixed resolution of 312 × 260 pixels^2. Besides, a light source was arranged behind the spray, and the high intensity fiber optic illuminators allow for the best possible viewing. For each experimental test, ten near-field spray images are captured and analyzed with MATLAB code. The variation of the macro spray parameters from shot to shot was within 7%. In addition, the average value of ten spray images was employed to represent the near-field spray characteristic. The common rail injection system was used to get different injection pressures (100 MPa, 120 MPa), and the ambient conditions are atmospheric pressure and room temperature respectively. The injection duration was kept the same as 2 ms. Besides, the fuel used in the test is the common diesel fuel with density of 830 kg/m^3, and the kinetic viscosity and surface tension are 2.57 mm^2/s at 40 °C and 27.3 mN/m respectively.

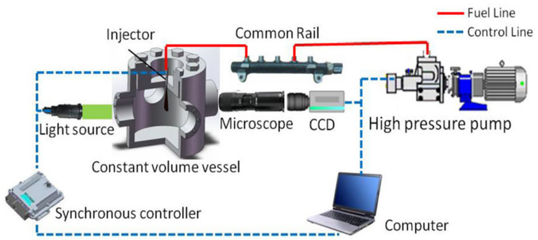


Figure 2. The near-field spray test platform.

3.2 *The near-field spray morphology processing*

MATLAB software was used for post-processing of digital near-field spray images, the macro-spray characteristic parameters such as projection spray area and spray cone angle (θ) were measured. The main workflow is shown in figure 3, threshold processing was applied to binary original spray images, and then the boundary of the binary image can be detected. For the spray projection area, the effective area pixels in the spray image are counted. Besides, the near-field spray cone angle was defined as the angle (θ) between the boundary lines of the near field spray contour.

4. Results and discussion

4.1 *The inner flow characteristics for the circular and elliptical orifices*

The calculation formula of discharge coefficient is shown in Eq. (1):

$$C_d = \frac{\dot{m}}{A\sqrt{2\rho(P_{in} - P_{out})}} \tag{1}$$

where $\dot{m}$ is the theoretical mass flow rate; P_{in} and P_{out} are the injection pressure and ambient pressure respectively; ρ is the fuel density; A is the cross section area.

Table 1. The geometrical parameters for diesel nozzle.

Orifice shape	Major axis (µm)	Minor axis (µm)	Exit area (µm^2)	Perimeter (µm)	Orifice length (mm)	Aspect ratio
Circle	160	160	20106.2	205.7	1.23	1
Elliptical	214.7	119.3	20106.2	533.0	1.23	1.8

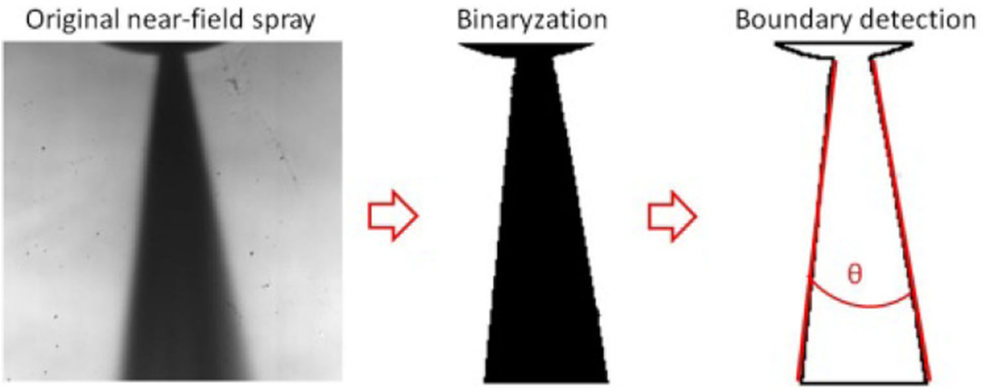


Figure 3. The definition of parameters for near-field spray morphology.

Cavitation number (KN) is an important dimensionless parameter used to study the development of cavitation characteristics inside the orifice. There are many definitions of cavitation number [30, 31], and the following definition is adopted as Eq. (2) in this study.

$$KN = \frac{P_{in} - P_v}{P_{in} - P_{out}} \tag{2}$$

where P_v is the saturation vapor pressure.

Figure 4 depicts the discharge coefficient for different cross section shapes orifices at various KN. The results show that the elliptical nozzle has higher discharge coefficient, indicating that using the elliptical nozzle is helpful to increase the orifice flow performance. Besides, the variation of the KN has little effect on the discharge coefficient. Because the hydraulic flip occurs in the nozzle, and the KN selected in this study are all within the scope of hydraulic flip conditions. It indicated that when the hydraulic flow appears in the orifice, and the discharge coefficient tends to remain unchanged with the decrease of KN, He *et al* [21, 31] also found the similar trend.

To analyze the influence of the inner flow on the near-field spray characteristics, we analyzed the vorticity magnitude for the circular and the elliptical nozzles. Present studies [27, 32] indicate that the turbulence vorticity at the nozzle outlet can speed up the near-field spray breakup. As shown in figure 5, the important finding is that the elliptical nozzle exit has larger vorticity magnitude than that of the circular one for all injection conditions. Also, the vorticity magnitude for all orifices increases as the injection pressure increase, suggesting the high injection condition is helpful to increase the turbulence vorticity. Besides, the vorticity magnitude represented the turbulence disturbance intensity, so it means that elliptical nozzle exit experiences larger turbulence intensity. Moreover, from the above results, it is inferred that the high turbulence vorticity of the elliptical orifice can effectively promote the breakup of near-field spray.

The intensity and distribution of cavitation inside the nozzle hole can affect the near-field spray characteristics greatly [33]. To further quantitatively analyze the influence of cavitation intensity at the nozzle outlet on downstream near-field spray patterns. The vapor phase fraction indicates

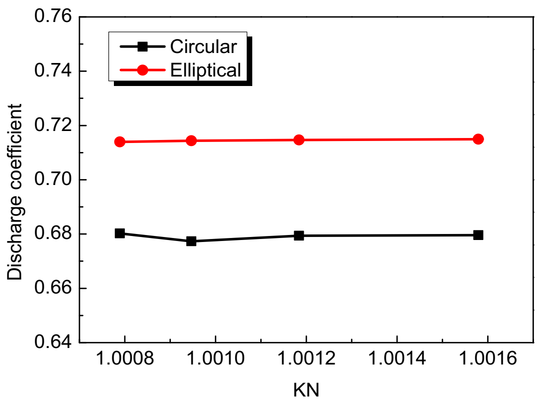


Figure 4. The discharge coefficient against KN for different cross section shapes nozzles.

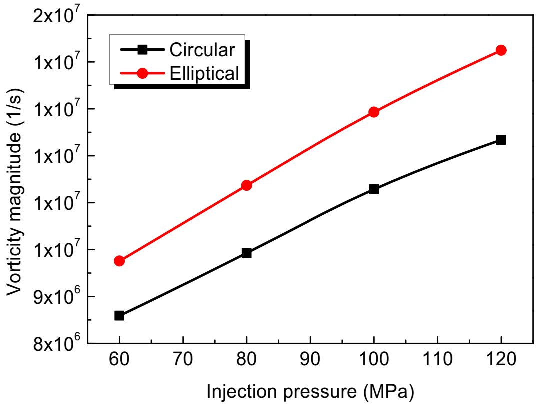
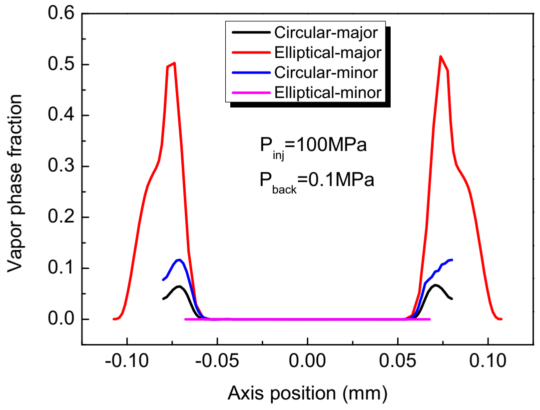
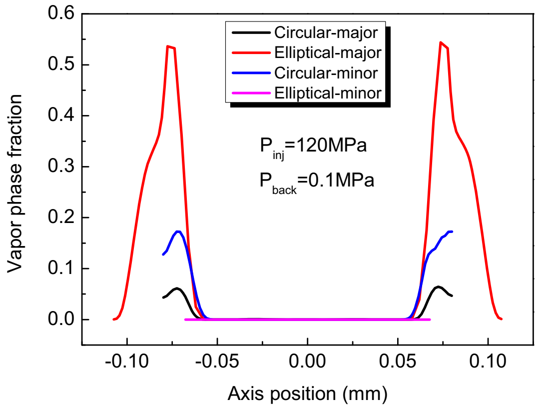


Figure 5. The orifice exit vorticity magnitude against injection pressure for circular and elliptical nozzles.

cavitation intensity, and vapor phase fraction on the major and minor axial were obtained by simulation method. Figure 6 depicts the vapor phase fraction along major and minor axis for various cross section shapes nozzles. From figure 6, at the major view plane, the values of vapor phase fraction appear two peaks in the near-wall area. It can also be seen from the figure 6 that the peak values of the vapor phase volume fraction increases as the injection pressure increases, and also the area with large vapor phase volume fraction increases. However, at the minor view plane, the vapor phase fraction of the elliptical orifice is near zero, the results showed that the elliptical nozzle outlet did not cavitate on the minor axis. Also, the vapor phase fraction for the circular orifice is higher than that of the elliptical orifice at the minor axis. Besides, the important finding is that the vapor phase volume fraction at major axis for the circular nozzle is smaller than elliptical nozzle. Desantes *et al* [34] pointed out that the high cavitation intensity can enlarge the initial spray angle. Hence, it is concluded from the existing results that the higher vapor phase volume fraction along the major axial of the elliptical nozzle is beneficial for increasing the near-field spray angle at the major axial plane.



(a) P_{inj}=100MPa



(b) P_{inj}=120MPa

Figure 6. The vapor phase fraction (cavitation intensity) along the major axis at different injection pressures. (**a**) $P_{inj} = 100$ MPa. (**b**) $P_{inj} = 120$ MPa.

4.2 *The near-field spray characteristics*

Figure 7 shows the development and variation of the near-field spray images under injection pressure of 120 MPa and atmospheric conditions. For the image acquisition area, the 2 mm spray downstream of the nozzle tip was photographed with a microscope magnifier, and the camera was set at the major and minor view planes of the elliptical orifice, we capture ten spray images at every injection time, figure 7 only shows the spray images taken by single injection at the major view plane. It can be seen from figure 7 that the expansion angle of the near-field spray with elliptical holes is larger than the circular one. Besides, the macroscopic morphology of near-field sprays changes little with the injection time, such as the spray cone angle and projected area of near-field sprays. To quantitatively analyze the difference of near-field spray parameters between the circular orifice and elliptical orifice, the macro characteristic parameters of the near-field spray were obtained by processing the spray images, and more details will be discussed in the next section.

Figure 8 compares the near-field spray angle of the circular hole and the elliptical hole at different injection pressures under atmospheric conditions. To obtain the data of the uncertainty quantification, the spray cone angle was measured ten times for each injection condition. The uncertainties associated with the measured spray cone angle is within 3%. It can be observed from figure 8 that the near-field elliptical spray cone angle at the major view plane is wider than the circular spray, for instance, the near-field spray cone angle for elliptical nozzle is larger than the circular nozzle by 48.2% at injection time of 1.1 ms under injection pressure of 120 MPa. However, at the minor view plane, the elliptical spray cone angle is smaller than that of the circular orifice at the near spray field, because the cavitation intensity for the circular orifice at the minor axis is constant higher than that of the elliptical nozzle. Also, for nozzle with same cross section shapes nozzles, the near-field spray angle increases slightly under the high injection pressure, but it is not obvious. In addition, as shown in figs. 5 and 6, the vorticity magnitude at the elliptical nozzle exit is constant more intense than that in circular nozzle, as well as the cavitation bubbles broken at the nozzle exit could induce many micro fluid jets and increase the turbulence disturbance at the nozzle exit, both of these factors contribute to significantly enlarge the near-field spray cone angle, particularly at initial injection progress. Also, the higher turbulence vorticity induced by the cavitation bubbles collapse at the orifice outlet could also increase the near-field spray breakup. Payri *et al* and Shinjo *et al* [35, 36] noted that the turbulence vorticity could increase

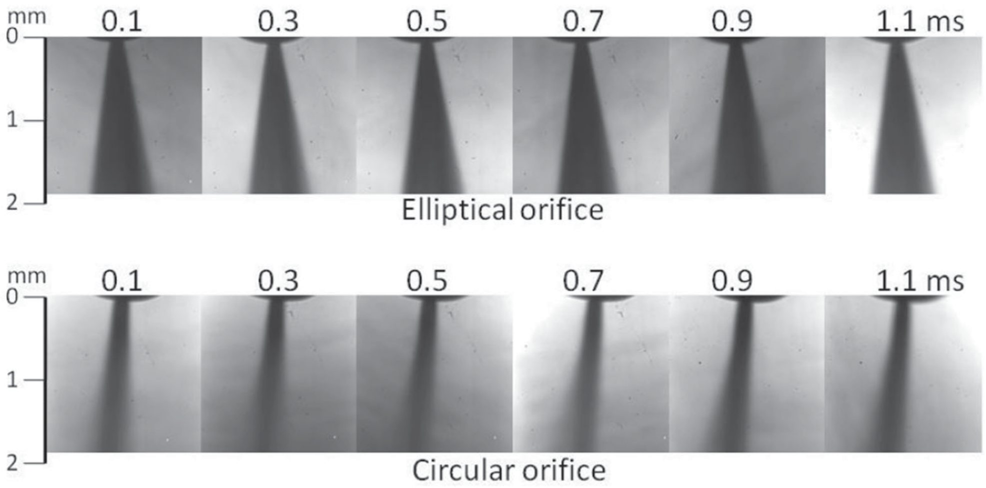
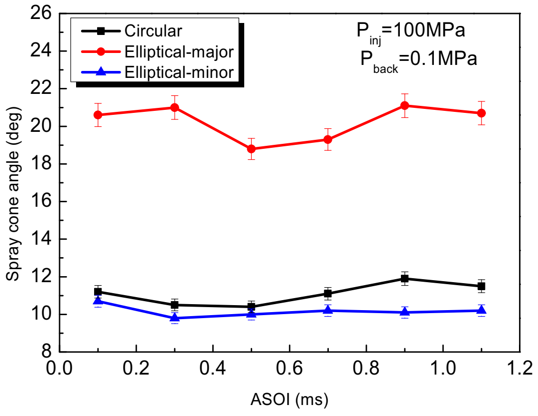
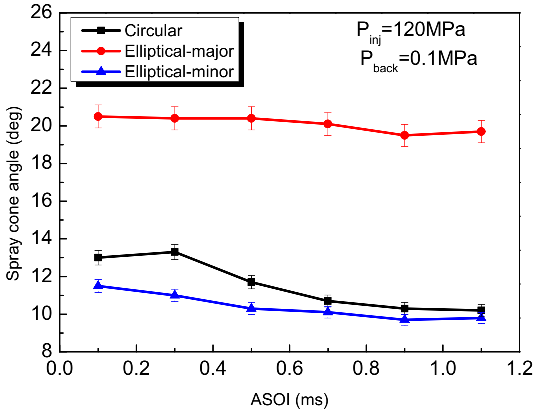


Figure 7. The near-field spray images against injection time for different cross section shapes orifices at the major view plane.



(**a**) P_{inj}=100 MPa

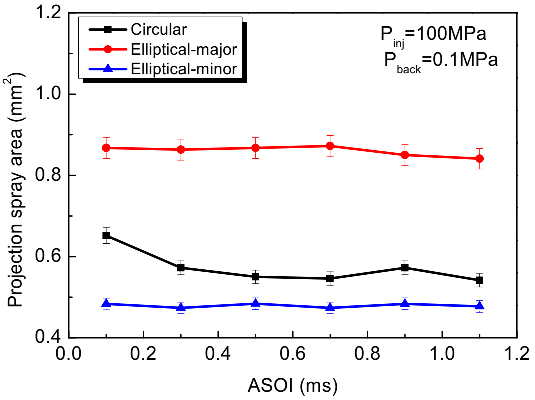


(**b**) P_{inj}=120 MPa

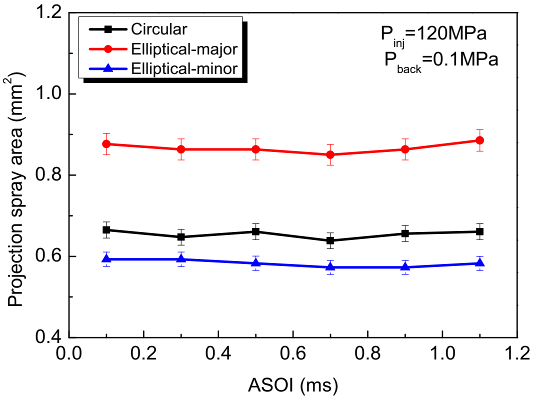
Figure 8. The near-field spray cone angle at the major and minor planes for different cross section shapes orifices. (**a**) $P_{inj} = 100$ MPa. (b) $P_{inj} = 120$ MPa.

the initial spray breakup. Therefore, it can be inferred that the using of elliptical orifice can increase the near-field spray quality greatly, and thus result in good atomization quality of the whole spray field.

The spray projection area can indicate the diffusion degree of the spray to a certain extent. The larger the spray area is, the better it mixes with the surrounding air [37]. The near-field spray projection area studied in this paper refers to the spray area within the field of vision, and the average value of ten images was obtained as the final spray projection area. The uncertainties associated with the measured spray cone angle is within 3.2%. Figure 9 presents the near-field spray projection area of the elliptical and the circular nozzles at various injection pressures and the ambient condition is atmospheric. Higher vorticity magnitude of the elliptical nozzle, higher intensity of turbulence disturbance was expected, which can accelerate the diffusion of the initial spray compared to the circular nozzle, and thus resulting in larger spray projection area for the elliptical near-field spray. Moreover, from the results of the cavitation distribution in figure 6, the cavitation intensity along the elliptical major axis direction is more intense than the circular one, and the cavitation development and collapse at the nozzle exit would increase the near-field spray cone angle at elliptical major axis. In turn, the spray projection area of the elliptical spray increased. Besides, during the stabilization of the spray, the spray projection area changes little under different injection pressure conditions, the present results trend agree with those of Wang *et al* [38]. However, at the minor view plane, the projection spray area of circular orifice is larger than that of the elliptical spray, because the vapor phase fraction intensity at the minor axis of the elliptical orifice is smaller as compared to the circular orifice.



(**a**) P_{inj}=100MPa



(**b**) P_{inj}=120MPa

Figure 9. The near-field spray projection area of circular and elliptical holes at the major and minor planes under different injection pressure conditions. (**a**) $P_{inj} = 100$ MPa. (**b**) $P_{inj} = 120$ MPa.

5. Conclusion

In this work, the results of near-field spray behaviors obtained from a spray visualization system and coupling with the inner cavitation patterns were studied for different cross section shapes injectors. The following conclusions are made:

(1) The elliptical nozzle has larger discharge coefficient, the increase in circulation ability was seen with the application of elliptical nozzle. The elliptical nozzle exit has higher vorticity magnitude at all injection conditions compared to those of circular nozzle. The increase of injection pressure could increase the turbulence vorticity magnitude at the nozzle exit for all geometrical nozzles.

(2) The cavitation is evenly distributed in the circular nozzle inner wall. While for the elliptical nozzle, the cavitation is mainly distributed in the major axis plane. The cavitation length along the major axis is longer than that at the minor axis for the elliptical nozzle.

(3) The elliptical nozzle near-field spray cone angles are wider compared to circular nozzle. Because the vorticity magnitude of the elliptical nozzle is constant higher and also the cavitation intensity along the elliptical orifice major axis is more intense than the circular nozzle, the cavitation development and collapse at the nozzle exit would enlarge the near-field spray angle.

(4) Higher vorticity magnitude at the elliptical nozzle outlet, higher intensity of turbulence disturbance was expected, which could accelerate the diffusion of the initial spray compared to the circular nozzle, and the elliptical spray has larger initial spray cone angle, both of these factors result in larger spray projection area for the elliptical near-field spray.

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