Experimental study of the effect of nozzle geometry on string cavitation and spray characteristics in real-size optical diesel nozzles

Zhou Chen[1]; Zhixia He*[2]; Wei Guan[1]; Qian Wang[1]; Genmiao Guo[1]; Han Zhou[1]

(1. School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, China;

2. Institute for Energy Research, Jiangsu University, Zhenjiang 212013, China)

Abstract

In this paper, A high speed CCD camera equipped with a long distance microscope was utilized to acquire the transient cavitating flow and spray characteristics in real-size optical diesel nozzles. The transient images of string cavitation and geometry-induced cavitation were captured in tapered-hole nozzles and cylindrical-hole nozzles, respectively. And the agglomerated geometry-induced cavitation was visually captured and analyzed for the first time. It was found that the string cavitation apparently increases the spray cone angle. However, the influence of geometry-induced cavitation on spray cone angle was negligible, but the influence of agglomerated geometry-induced cavitation on spray cone angle was prominent. Furthermore, the larger nozzle hole L/D ratio means the stronger string cavitation, and spray cone angle is also obviously increased. Finally, the difference of string cavitation and spray characteristics between Min-sac and VCO nozzle was analyzed in details.

Keywords: real-size optical nozzle; nozzle geometry; string cavitation; spray characteristics

1. Introduction

The spray atomization characteristics of the diesel injector plays an essential role for the good spray combustion and pollutant emissions performance. And the spray atomization characteristics are directly influenced by internal flow characteristics of the diesel nozzle. Many scholars have investigated the internal flow of diesel nozzles. Many years ago, Arcoumanis et al.[1] investigated the cavitating flow in real-size multi-hole diesel injector nozzles and found the differences of flow characteristics between the real-size nozzles and scaled-up transparent nozzles. But all the injection experiments were performed under low injection pressure which maximum pressure was not more than 35MPa and could not represent real fuel injection events. Gavaises M, and Winterbourn M[2][3] utilized the scaled-up nozzle model to study the effects of the needle motion on the transient characteristics of the nozzle cavitating flow in which the geometry-induced cavitation and string cavitation was captured with a conventional CCD camera. Experiments indicated that the link between cavitation and turbulence in the sac volume and the anticipated enhancement of turbulence through the onset of cavitation was identified only at the entrance of the nozzle hole. However, the scale effects could not be neglectful in scaled-up nozzle models. Mitroglou N et al. [4][5] studied the cavitating flow in diesel optical nozzles as well and found the initial bubbles sucked into nozzle holes and string cavitation phenomenon. Sun Z. Y et al.[6] investigated the effects of the pressure difference, roundness of nozzle inlet, orifice coefficient, orifice length to diameter, and the roughness of orifice inner wall on geometry-induced cavitation by CFD. Although the investigations have made large progress, there is little mention of vortex induced string cavitation and its effect on spray characteristics. He Z et al.[7] subsequently found that the string cavitation has a strong relationship with the location of needle, the injection pressure, and the shape of sac. David Sedarsky, Ding H, and Crua C[8][9][10] investigated diesel spray formation at initial stage from single-hole metal nozzles, the spray transient fluctuation and mushroom head, respectively. However, because of absence of nozzle internal transient flow visible data, above spray phenomena can not be well explained and all spray characteristics have not been well connected with the internal flow. In general, previous studies have made lots of interesting achievements, but the occurrence regularity and flow characteristics of string cavitation and also its effect on subsequent initial spray structure are still not clear and deserved to further investigate for understanding better.

In this paper, the real-size transparent tapered-hole nozzle tip equipped to the high pressure common rail fuel injector was made for visual investigations of string cavitation characteristics with considering variations of nozzle hole, such as L/D ratio, hole tapered coefficient K-factor, and nozzle sac geometry and their effects on initial spray structure.

2. Experimental setup and methodology

Based on the 250 MPa common rail injection system (BITEC-GY250-2), the nozzle flow and spray visualization experiment system was established shown in Fig.1. According to the shadow photography, the tested nozzles were placed between the LED light and the high speed CCD camera (FASTCAM SA-Z) with a long distance microscope (QM-1, QUESTAR). The maximum camera shooting rate is 210,000 frames per second with 384×160 pixels. For the sake of capturing higher resolution images with larger shooting rate, the shooting rate is 100,000 frames per second and the images have a resolution of 640×280 pixels in this experiment.

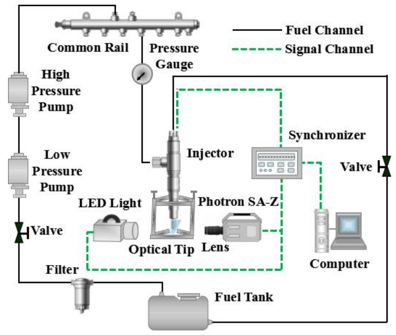


Fig.1. Schematic of visualization system for internal flow

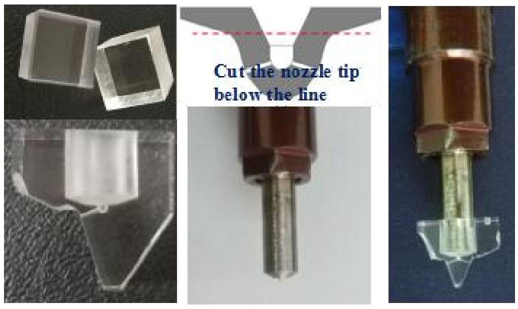


Fig.2. Origin diesel nozzle and real-size optical nozzle

The original metal injector nozzle tip was cut and replaced by the real-size optical nozzle tip (Fig.2), so that the transient cavitating flow inside the nozzle could be captured visually. For guaranteeing the good sealing performance between needle and needle seat of nozzle, the cutting position must be below the sealing line. The optical nozzles were made of acrylic, because of its good light transmittance (>92%), good compression resistance and the similar refractive index (1.48~1.52) to diesel fuel (1.49~1.51). The optical nozzles manufacturing were completed by precision drilling machine. Subsequently, the optical nozzle tip and injector could be assembled by a fixture. Specifications of the test nozzles were shown in Table 1. The K-factor was calculated by the equation (the units are micron): K-factor = (D_{in} − D_o)/10. By shadow photography, when light goes through the interface of vapor (cavitation and bubbles) and liquid diesel, light refraction happens so that vapor phase presents black as a result of large differences between diesel liquid and vapor phase. On the contrary, the diesel fuel liquid phase represents white because of similar refractive index between liquid diesel and acrylic nozzle tip.

Table 1. Specifications of the test nozzles

Nozzle number	Hole number	D_{in} /mm	D_o /mm	L/D_o ratio	Nozzle type	K-factor
1	1	0.18	0.18	10.5	Min-sac	0
2	1	0.18	0.18	6.5	Min-sac	0
3	2	0.289	0.207	9.6	Min-sac	8.2
4	2	0.289	0.216	7.9	Min-sac	7.3
5	1	0.306	0.216	10.5	Min-sac	9
6	1	0.306	0.216	10.5	VCO	9

All experimental data such as needle lift, spray cone angle, intensity of string cavitation (I_{string}) was obtained and after-treated by MATLAB code. The spray cone angle was taken for example. Firstly, the MATLAB code could captured the interface of fuel spray and ambient air with two millimeters from the outlet. Based on this interface, the two fitting lines could be created, and then using slopes of fitting lines, the spray cone angle can be calculated. Furthermore, the intensity of string cavitation can be calculated by the following equation: $I_{string} = S_{string} / S_{hole}$ (S_{string} means the area of string cavitation, S_{hole} means the area of nozzle hole in the nozzle flow 2d image).

3. Results and discussion

3.1 Transient cavitating flow in cylindrical hole nozzles

The transient cavitating flow and spray images during a whole fuel injection period with the injection duration of 2000 μs under the injection pressure of 60 MPa in nozzle 1 were shown in fig.3. The graphs below the purple line show the enlarged nozzle orifice flow images of 4 typical injection times (430us, 900us, 2070us and 2090us) for illustration a kind of special cavitation agglomeration phenomena. Paper chose the stage that the bubble suction happened as the start of injection. It is obviously to see that during initial injection stage, the initial bubbles are existing in the nozzle orifice and would experience the process of bubble suction and bubble compression on account of sudden movement of needle at the opening stage. Then the geometry-induced cavitation appears and extends to the outlet (260 μs). And it is interesting to see that the geometry-induced cavitation could be agglomerated (360 μs), accompanied with markedly increasing of spray cone angle. When it develops to 430~490 μs, the phenomenon of agglomerate geometry-induced cavitation becomes more aggravating and the spray cone angle is increased even to 29° , later further up to 31° , because of occurrence of the string cavitation (500 μs) showed, which is almost three times of it (10°) at higher needle lift stage. The flow and spray at the needle closing stage shows the similar results with that at the needle opening stage. Therefore, the agglomerate geometry-induced cavitation here is also regarded as a kind of string cavitation which is transformed from geometry-induced film cavitation with influence of vortex flow in the nozzle orifice. Because the vortex flow was much stronger at needle opening & closing stage corresponding to the low needle lift causing the narrow flow channel, the vortex flow and the turbulence intensity may also strengthened. In other words, the vortex flow and string cavitation agglomerates geometry-induced cavitation to form this kind of string cavitation in the axis vicinity of nozzle hole. Just similar with Andriotis' study[11] that vortex flow agglomerated pressurized air.

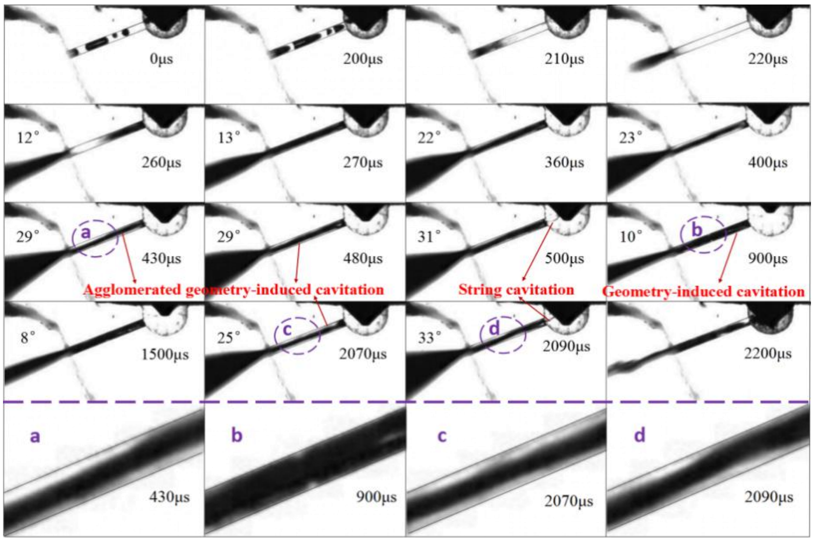


Fig.3. Transient cavitating flow in single cylindrical orifice nozzle with mini sac (60 MPa)

The relationship between the spray cone angle and string cavitation variations with time during needle movement was shown in Fig 4. It is not hard to find that the increase of spray cone angle is synchronized with occurrence of string cavitation. However, during the full opening stage of needle, although the geometry-induced cavitation exist all the time (900 μs &1500 μs in Fig.3.) , the spray cone angle was evidently smaller than that during the opening & closing stage. The results manifest that it is the string cavitation but not geometry-induced cavitation accelerates the increase of spray cone angle.

3.2 The effects of nozzle orifice L/D ratio on string cavitation and spray characteristics

The effects of nozzle orifice L/D ratio on string cavitation and spray characteristics were investigated by nozzle 1 and nozzle 2 with cylindrical holes and the injection duration is 2000 μs under injection pressure of 50 MPa (Fig.5.). The experimental results indicated that with decreasing of the L/D ratio, the string cavitation is more prevailing. And the spray cone angle with smaller L/D ratio is almost larger than that with larger L/D ratio. When the fuel flows past the small-L/D-ratio nozzle hole, because of low flow resistance, the fuel velocity would be higher which could strength the vortex and turbulence intensity. As a result, it presents prevailing string cavitation and a larger spray cone angle.

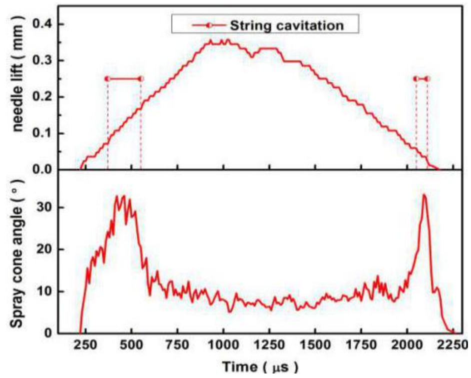
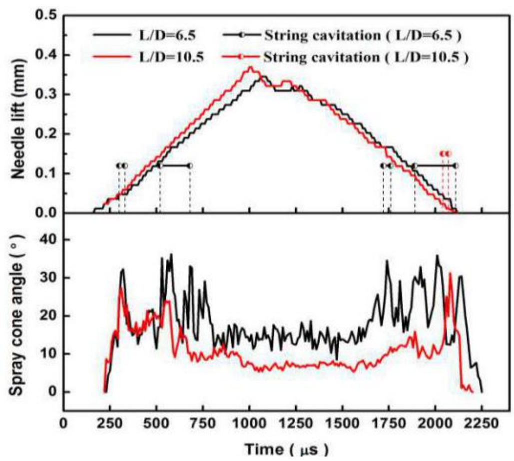


Fig.4. Relationship among needle lift, spray cone angle and the string cavitation in single cylindrical orifice nozzle with mini sac (60 MPa)

Different from nozzle 1 and nozzle 2, nozzle 3 and nozzle 4 have the tapered holes. The influence of hole L/D ratio on string cavitation and spray characteristics were investigated once again in these tapered-hole nozzles with the injection duration of 1800 µs under injection pressure of 80 MPa shown in fig.6. The curves manifest the similar results as previous results in cylindrical-orifice nozzles shown in fig.5. Obviously, the intensity of sting cavitation has been strengthened a lot inside the nozzle hole with smaller L/D ratio. Certainly, the spray cone angle was larger as well on account of stronger sting cavitation.



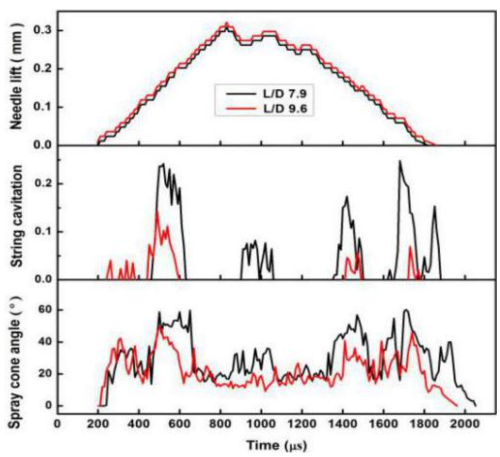
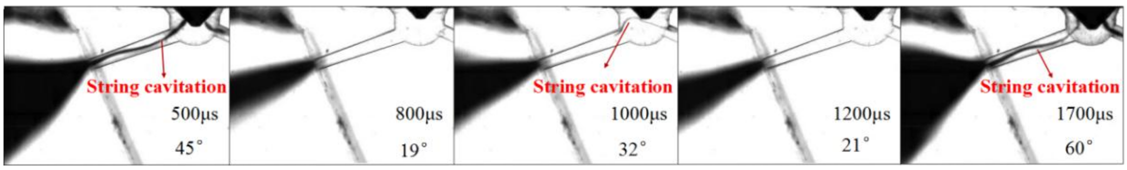
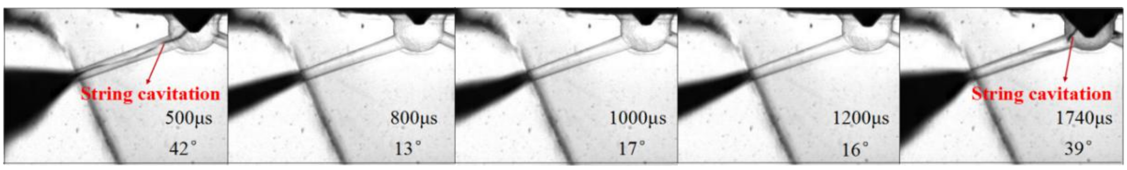


Fig.5. Effects of L/D ratio on string cavitation in cylindrical nozzle (50 MPa)   Fig.6. Effects of L/D ratio on string cavitation in tapered nozzle (80 MPa)

Benefited from the suppression of geometry-induced cavitation in the tapered nozzle hole, the string cavitation were clearly obtained without the interference of geometry-induced cavitation (Fig.7.). It is easy to see that the tapered nozzle could preferably suppress the geometry-induced cavitation. And the intensity of string cavitation in small-L/D-ratio nozzle was much stronger. Besides, during the lower needle lift stage (500 µs & 1700 µs), the string cavitation is originated from needle seat. However, during the higher needle lift stage (1000 µs), the string cavitation is originated from one hole and extends through sac volume into the other hole and can be called hole-to-hole string cavitation, and in this case the spray



a) L/D = 7.9



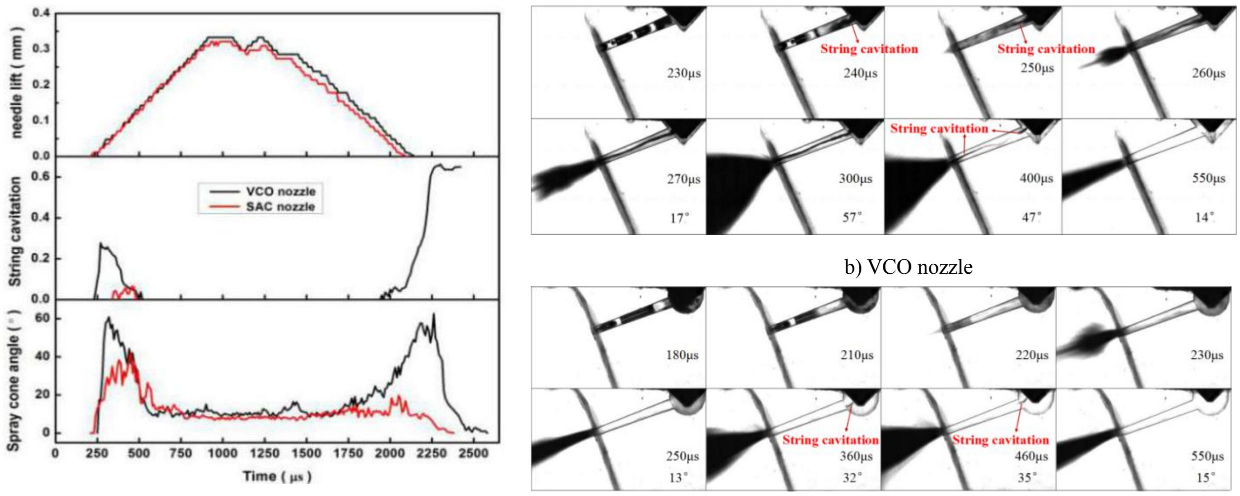
b) L/D = 9.6

Fig.7. String cavitation and spray characteristics of tapered nozzles with different L/D ratios (80 MPa)

cone angle is smaller than the former on account of weaker string cavitation. One of reasons could be that the higher needle lift made larger room for fuel in min-sac. Therefore, the intensity of vortex and turbulence was weaker. Certainly, the string cavitation is hard to develop and extend to outlet, and the obtained spray cone angles are smaller. However, things are different for a large-L/D-ratio nozzle as shown in fig.7(b). Except that the needle-originated, string cavitation is a bit weaker at the low needle lift compared to that in the small-L/D-ratio nozzle, the hole-to-hole string cavitation doesn’t occur at all in large-L/D-ratio nozzle during the high needle lift stage (1000 μs). That can be attributed to the higher flow resistance for the longer orifice of the nozzle which means a lower fuel velocity and weaker turbulence intensity.

3.3 Transient cavitating flow characteristics in Min-sac and VCO nozzles

Utilizing nozzle 5 (Min-sac type) and nozzle 6 (VCO type) with the fuel injection duration of 2000 μs under injection pressure of 60 MPa, the effect of nozzle sac geometry on transient cavitating flow characteristics investigated shown in Fig.8. Both optical nozzles have only one tapered orifice, in which only the string cavitation originated from needle valve exists at low needle lift. As shown in fig.8(a), the string cavitation in the VCO nozzle occurs earlier, and maintained a longer time than that in the Min-sac nozzle. Accordingly, the spray cone angle is comparatively larger in the VCO nozzle than that in Min-sac nozzle. The flow experiences extremely violent flow transition at the inlet location of VCO nozzle orifice, so that the vortex and turbulence intensity and the local low pressure were strengthened here. As a result, the stronger cavitation spontaneously appears.



a) String cavitation and spray in the Min-sac and VCO nozzles c) Min-sac nozzle

Fig.8. The effect of nozzle sac geometry on transient cavitating flow characteristics (60 MPa)

The transient internal flow and corresponding spray development of the Min-sac nozzle and VCO nozzle with a single tapered orifice were shown in fig.8(b) and fig.8(c), respectively. Firstly, in fig.8(b), the string cavitation inception appears at 240 μs almost simultaneously with the beginning of bubble compression in the VCO nozzle. And it is interesting that the initial bubbles could be emerged into the vortex flow and form a part of string cavitation. When the string cavitation develops to the outlet, the spray cone angle increased immediately. However, in the Min-sac nozzle, the string cavitation inception appears later at 360 μs shown in fig.8(c). The main reason for this difference is the stronger vortex and turbulence flow in VCO nozzle. Certainly, the initial bubbles, providing a great number of gas nuclei, could stimulated the string cavitation inception. Compared to the VCO nozzle geometry, the Min-sac nozzle has a comparatively larger sac volume, and then the flow transition is much weaker. Besides, in the VCO nozzle, with the increasing of needle lift, the string cavitation is gradually weaker and weaker after injection time of 300 μs, and then it begins to vanish after injection time of 400 μs, firstly at middle location of nozzle orifice, and later at orifice outlet location, inlet location followed. However, the string cavitation originated from needle seat in the Min-sac nozzle only develops a little to the inlet of nozzle orifice and keeps a very short period and then disappears.

4. Conclusion

In this paper, the real-size optical nozzle tip with tapered orifice was made and equipped to the high pressure common rail injector for visualization of string cavitation characteristics. The effects of nozzle geometry on string cavitation and spray characteristics were investigated and then the important conclusions are summarized as follows:

1) The vortex flow and string cavitation could agglomerate geometry-induced cavitation to the axis vicinity of nozzle hole. And the agglomerated geometry-induced cavitation contributes to the larger spray cone angle as well as the string cavitation does.
2) The increase of spray cone angle is synchronized with occurrence of string cavitation. It is the string cavitation but not geometry-induced cavitation has a larger contributions to the increase of spray cone angle.
3) The tapered nozzle could preferably suppress the geometry-induced cavitation. The nozzle orifice L/D ratio plays an essential role for occurrence and strength of string cavitation. Small L/D ratio means more prevailing string cavitation in the nozzle and a larger spray cone angle.
4) Owing to the stronger vortex and turbulence intensity, the string cavitation appears earlier and is much stronger in the VCO nozzle, and could maintain a longer time than that in the Min-sac nozzle.

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