Experimental Study on Correlation between String Cavitation and Spray Angle of Diesel Injector Nozzles with Tapered Orifice

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Abstract

The string cavitation characteristics in diesel nozzle and its influence on spray characteristics were investigated with visualization experiments of different scaled-up optical nozzles. The 3D printing and machining were used to manufacture the 5-times, 8-times and 10-times enlarged transparent nozzles, and comparisons of the string cavitation characteristics in these three nozzles were performed. Effects of injection pressure and needle lift on string cavitation characteristics was analyzed. During the low needle lift stage, string cavitation, originated from the needle tip surface always, shows a thicker form and stronger intensity and causes a large spray angle. With the needle lifting up, the needle-originated string cavitation would vanish and could be displaced by the hole-to-hole string cavitation in a slimmer form with weaker influence on spray angle. When the injection pressure is high enough, geometry-induced cavitation occurs even in this tapered-orifice nozzle. A larger spray angle because of occurrence of needle-originated string cavitation under low needle lift provides a reasonable explanation on the sudden increase and fluctuation of the spray angle at the beginning and end of the injection period. The research indicates that the spray angle has a strong relationship with the string cavitation development and thickness of string cavitation at the outlet; the hysteresis was observed for the string cavitation influencing the atomization process which can be related to the time of cavitation bubble collapsing outside and the inertia of fluid motion inside.

Keywords: diesel injector nozzle, string cavitation, visualization, tapered orifice, spray angle

1. Introduction

Cavitation phenomenon commonly exists in the diesel injector nozzles which may positively accelerate the spray break-up process and simultaneously negatively incur the spray instability. Understanding cavitation phenomena well is quite important to a better spray atomization and air-fuel mixture, especially the special vortex-induced string cavitation and its effect on spray are still known less. Therefore, it is necessary to conduct the further investigation on correlation between string cavitation and spray angle in diesel nozzles.

Soteriou C (1995), Arcoumanis (2000), Gavaises (2002), Andrew (2008), Andriotis A (2008), et al.[1-5] used the scaled-up model of the real injector nozzle to experimentally study the effects of the needle motion on the transient characteristics of the nozzle two-phase cavitationg flow. Besides the existence of the normal cavitation induced by the geometrical features at the entrance of the orifice, another special string cavitation induced by the internal vortex flow exists in the diesel engine nozzle. The normal cavitation exists around the internal wall of the cylindrical orifice in the visualization experiment with transparent nozzle, which always interrupt the observation of the string cavitation normally developing in the center of the orifice[6-8].So that, the research on the string cavitation is very limited. The present work designs three different dimensions of the transparent nozzles with tapered orifices to eliminate the occurrence of the geometry-induced cavitation and researched the occurrence regulation, intensity and transient characteristics of the string cavitation, and its influence on the spray.

2. Experimental equipment and methodology

Visualization of the string cavitation was performed in three different dimensions of the transparent nozzles with tapered orifices. The sketch of flow visualization and spray test stand for nozzle is depicted in Fig. 1(a), which consists of three parts: the fuel injection system, the fuel supply system and the imaging acquisition system. The injector makes the overall geometric proportions, which on the basis of the original size injector. The nozzles were processed with transparent material of acrylic. They are connected with the upper part of the injector by flange. The injection pressure is provided by the constant pressure tank. The imaging acquisition system mainly includes a CMOS Camera (FASTCAM SA-Z) equipped with a NIKKOR LENS(AF Micro-Nikkor 200mm f/4D IF-ED) and a high-power LED

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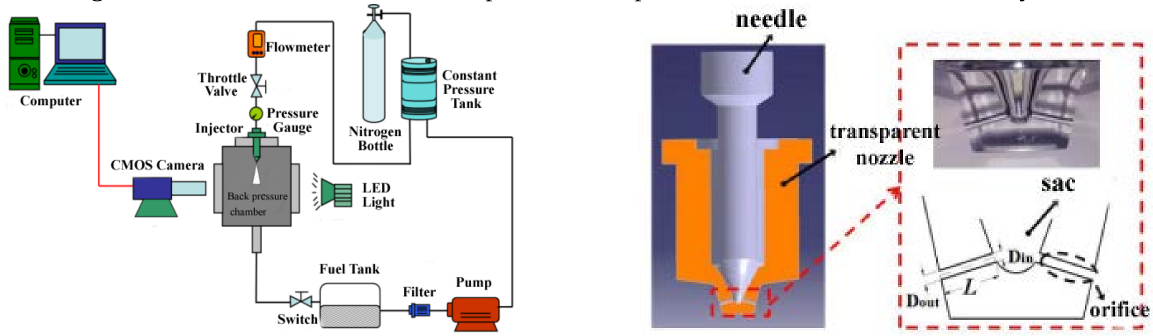
light as a lighting source. During the experiment, the capturing speed was set to 20,000 frames per second and the obtained images have a resolution of 1024 × 1024 pixels. The experiment was conducted under steady state condition.



(a) (b)

Fig. 1(a) Sketch of flow visualization and spray test stand for nozzle, (b) Sketch map of transparent nozzle.

The scaled-up optical nozzle is the critical component in this experiment for achieving high quality images of cavitating flow inside the nozzle. The transparent nozzle was made by 3D printing and high precision machining technology, as shown in fig.1(b). The orifice conicity of nozzle can be precisely controlled by this method. Two orifices were arranged symmetrically on the nozzles, and the sizes of the two orifices were the same. The geometrical parameters of the three diesel injector nozzles with tapered orifice were given in Table 1.

Table 1 geometrical parameters of double hole of nozzle

Nozzle magnification	Orifice inlet diameter D_{in}(mm)	Orifice outlet diameter D_{out}(mm)	Length of orifice L(mm)	K_{factor}	Inclination angle of orifice Ø (°)
5-times	1.05	1.0	5	+1	75
8-times	1.68	1.6	8	+1	75
10-times	2.1	2.0	10	+1	75

The obtained typical images of multiphase flow by shadow photography is shown in fig.2. The tested nozzles were placed between the LED light and the high-speed COMS camera. When light goes through the interface of vapor phase and liquid diesel, the light refraction happens so that vapor phase presents black as a result of different refractive index between diesel liquid and vapor phase. On the contrary, the diesel fuel liquid phase represents white on account of similar refractive index between liquid diesel and acrylic nozzle. In addition, the spray presents black because light is overshadowed by spray droplets. In the nozzle, the string cavitation can be originated from needle tip surface and then develops to orifice exit and it can also exist in the sac then connects two orifice. In terms of needle-originated string cavitation, once it appears, there are two typical shapes. One is complete penetration type and the other is non-complete penetration type.

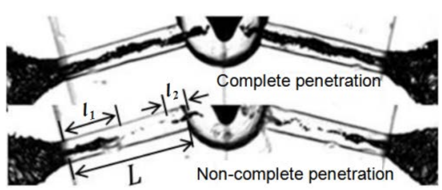


Fig. 2 Sketch map of string cavitation development

When analyzing string cavitation from space dimension, the degree of needle-originated string cavitation development Q is defined for reflecting the development degree of the transient string cavitation, as follows:,

$$Q = \frac{l}{L} \tag{1}$$

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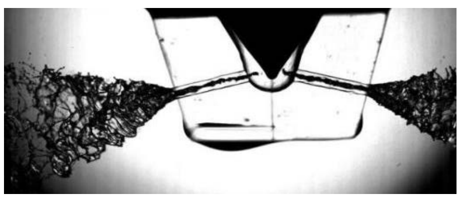
$$l = l_1 + l_2 \quad (2)$$

where l is the total length of the development of cavitation along the axis of the hole, L is the length of orifice, l_1 and l_2 are separated string cavitation length shown in fig.2.

3. Results and Discussion

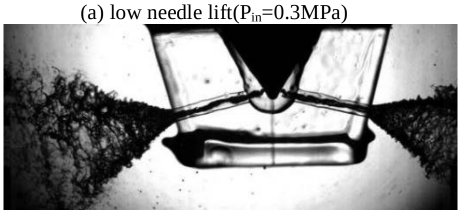
3.1 The effects of injection pressure and needle lift on string cavitation characteristics

The string cavitation inside the 10-times enlarged transparent nozzles with mini sac at different needle lift under the different injection pressures was shown in fig.3. When the injection pressure is 0.3MPa and the needle lift is low (fig.3 a), the string cavitation originates from needle tip surface and appears very thick and have a larger influence on spray angle. With lifting up of the needle, the needle-originated string cavitation gradually disappears and transform into the hole-to-hole string cavitation with a weaker development degree (fig.3 b), and then has just very limited influence on spray. When the injection pressure increases from 0.3MPa to 1.0MPa (fig.3 c & fig.3 d), the effect of needle lift on string cavitation is similar. While for a higher injection pressure, the string cavitation is thicker and induced a larger spray angle with the low needle lift. At a high needle lift, besides hole-to-hole string cavitation, geometry-induced cavitation also occurs and is mixed with string cavitation, then further influence spray together. Those diversities of internal flow and spray angle could be attribute to the stronger intensities of vortex and turbulence flow which caused by low needle lift or high injection pressure.

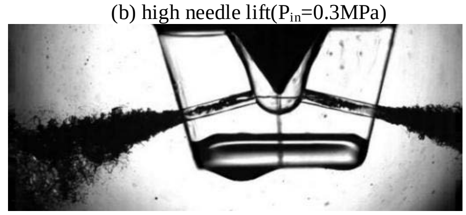


(a) low needle lift(P_{in}=0.3MPa)

(b) high needle lift(P_{in}=0.3MPa)

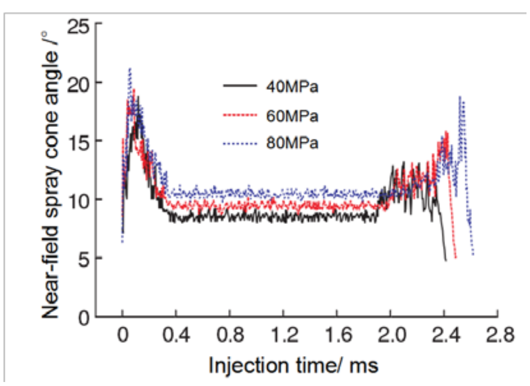


(c) low needle lift(P_{in}=1.0MPa)

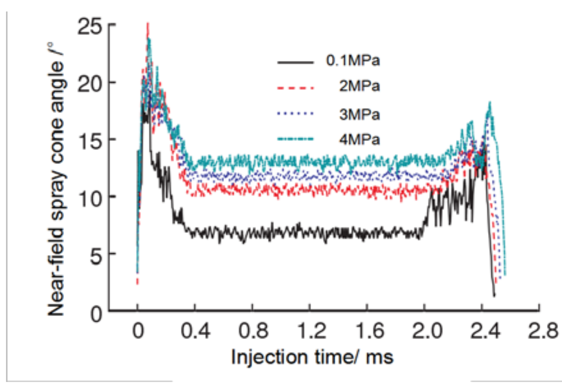


(d) high needle lift(P_{in}=1.0MPa)

Fig.3 needle-originated and hole-to-hole string cavitation and their influence on spray angle



a. Different injection pressures (P_{back}=0.1MPa)



b. Different back pressures (P_{inj}=60MPa)

Fig.4 Change of near-field spray cone angle with time under different working conditions

A larger spray angle at low needle lift and a smaller spray angle at high needle lift can illustrate the two peaks of spray angle at initial period and end period of fuel injection process corresponding to the low needle lift, as shown in

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fig.4[11]. The spray angle data was got from metal nozzle of the high pressure common-rail injection system under different injection pressures and back pressures.

3.2 The effect of cavitation development on spray angle

Fig.5 shows the relationship between the development of string cavitation and the spray angle during the steady injection process. It can be found that the spray angle increases remarkably with the string cavitation development. Factually, the fluctuation of the development degree of the string cavitation is synchronous with the fluctuation of spray angle. Therefore, it can be deduced that the string cavitation boosts the spray angle. However, the fluctuation of spray angle is comparatively hysteretic with that of the development degree of the string cavitation, this phenomenon is related to the time of cavitation bubble collapsing at outlet.

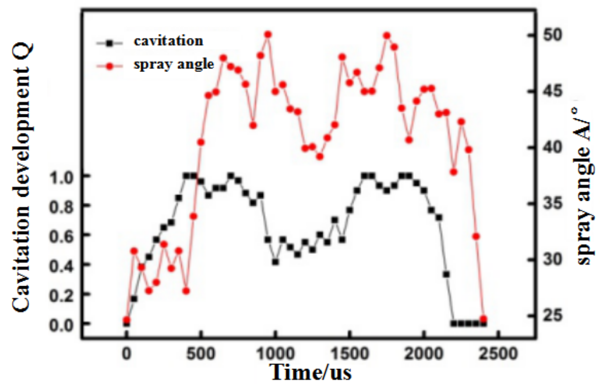

Fig. 5 The influence of cavitation development on spray angle (Pinj=0.18MPa)

3.3 The effect of string cavitation thickness on spray angle

In order to analyze the effect of string cavitation thickness on spray angle, the two-dimensional area of the string cavitation at the outlet of the orifice was presented to characterize the three-dimensional rotational cavitation bubble volume, as shown in fig.6. The rectangular region of one-third orifice length along the direction of the orifice was picked up, and after-treated by MATLAB code to compute the binary value of the image. Although there are some errors in the representation of three-dimensional volume with -two-dimensional images, the string cavitation of three-dimensional axial rotation can be approximately considered to be an axisymmetric form. Three kinds of enlarged transparent nozzles test images were treated with binary image processing. Pixel with gray value of 0 is selected to reflect the string cavitation thickness in the near-exit area of the orifice, and can be coupled with the measurement value of the spray angle.

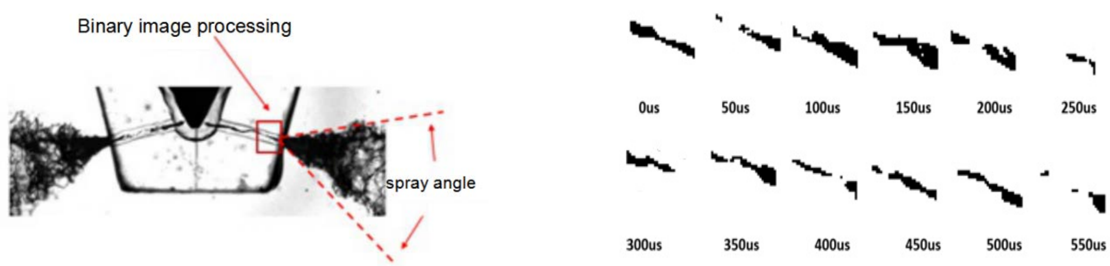

Fig. 6(a) Sketch map of binary image processing, (b) image of the string cavitation in 5-times scale-up nozzle after binary image processing

The influence of string cavitation thickness on spray angle in different scale-up nozzles is depicted in fig.7. It can be found that the fluctuation of the string cavitation thickness at the outlet of orifice in different enlarged nozzles is similar to that of the spray angle. The liquid phase perturbation, caused by the cavitation bubble collapsing at outlet, is one of the factors that boost spray angle. Additionally, the reason of the fluctuation variation could be that both the string cavitation and vortex motion contribute to the external spray. Besides, as the nozzle magnification increases,

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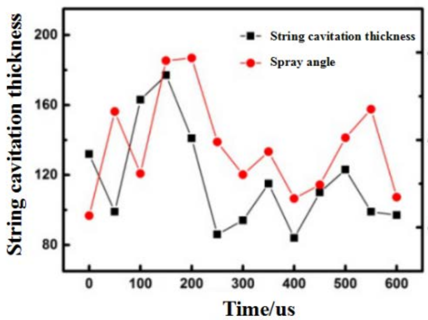
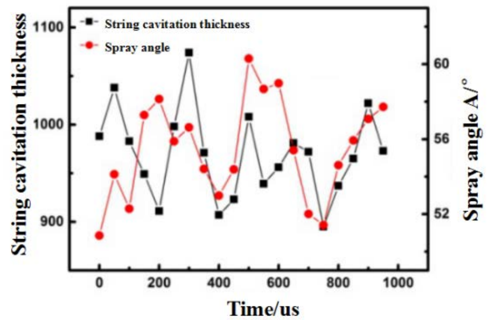
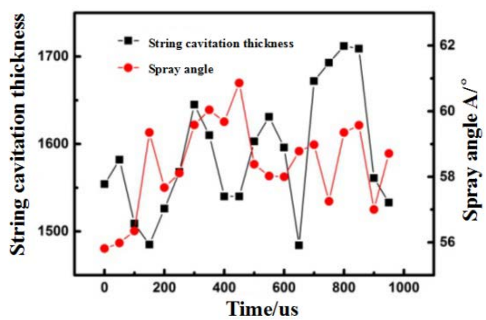
the frequency of fluctuations become larger and the spray angle become larger as well. The higher of magnification means the greater intensity of string cavitation. That could bring a shorter time of cavitation bubble collapsing at outlet, as a result, a slightly hysteresis phenomenon was obtained.



(a) 5-times scale-up nozzle



(b) 8-times scale-up nozzle



(c) 10-times scale-up nozzle

Fig. 7 The influence of string cavitation thickness on spray angle in different scale-up nozzles(Pinj=0.8MPa)

4. Conclusion

In this paper, an experimental visualization device and enlarged transparent diesel nozzles have been adopted to obtain the images of string cavitation inside the nozzle with different injection pressures and different needle lift. The obtained conclusions are summarized as follows:

1. Different needle lifts leads to different flow channel structure. Flow channel structure under the low needle lift will cause more intense vortex motion, resulting in a thicker string cavitation originating from the needle tip surface and causing the big spray angle. With lifting up of the needle, a thinner hole to hole string cavitation appears, and then has just very limited influence on spray. This provides a reasonable explanation on the scene of the sudden increase and fluctuation of the spray angle at the beginning and end of the injection period.

2. External spray angle has a strong relationship with the string cavitation development degree and string cavitation bubble thickness at the exit; the hysteresis observed while the string cavitation influencing the atomization is not only related to the time of cavitation bubble fracturing outside and may also be related to the inertia of fluid motion inside. As the magnification increases, the frequency of fluctuations become faster and the hysteresis phenomenon become weaker.

Acknowledgments

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