OPTICAL EXPERIMENTS OF STRING CAVITATION IN DIESEL INJECTOR TAPERED NOZZLES

by

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Flow inside the diesel nozzle is crucial to spray, combustion, and emissions. This work aimed to improve the understanding of effects of internal fuel-flow on diesel spray, especially the special string cavitating flow. Optical experiments were employed for characterizing the formation of string cavitation inside the transparent scaled-up tapered diesel orifices. Simultaneously, the corresponding evolution of spray cone angles were obtained. Results show that there were two origins of the string cavitation, which were originated from inlet and outlet of the orifice, respectively. Moreover, there were two typical development processes of the string cavitation between hole and hole, which were defined as type-A and type-B string cavitation. Furthermore, effects of string cavitation were analyzed: it could trigger the geometry-induced cavitation and make a sharp increase of spray cone angle. Finally, the relationships between the occurrence regularity of string cavitation, the needle lift and the injection pressure were revealed by comparison of different needle lifts and different injection pressures.

Key words: *diesel, optical, tapered nozzle, string cavitation, spray*

Introduction

Common rail fuel injection system has been widely employed in the Diesel engines for achieving high efficiency and low emissions. Additionally, the injector is the significant part in determining the characteristics of inside-nozzle flows. As well as, processes of the fuel atomization and spray are largely affected by the internal cavitating flow of the diesel nozzle [1-3]. Therefore, many experimental and theoretical investigations have focused on the cavitating flow inside the engine injector nozzles. It is found that there are two mechanisms for cavitation inside the diesel nozzles. According to the generation mechanisms, the cavitation can be clarified into dynamically-induced cavitation and geometry-induced cavitation [4, 5].

The geometry-induced cavitation is a well-known phenomenon initiating at sharp corners where the local pressure may fall below the saturated vapor pressure of the fuel. Many investigations have focused on the geometry-induced cavitation. Kato *et al.* [6] measured the pressure distributions in the nozzle sac and orifices. They found that geometry-induced cavita-

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tion at the hole inlet was sensitive to both the nozzle sac geometry and the inlet hole configuration. Payri *et al.* [7] reflected that the geometry-induced cavitation could lead to an increase in the spray cone angle and the flow outlet speed. He *et al.* [8] analyzed influences of the nozzle hole shape on internal flows and near-nozzle spray behaviors. Som *et al.* [9] studied the effects of tapered orifice on spray, combustion and emission characteristics under Diesel engine conditions according to results of the spray coupling with the internal flow simulations. The tapered hole greatly modified the pressure distribution at the hole entry and prevented the formation of the geometry-induced cavitation. The string cavitation formed by the vortex flow is a dynamically-induced cavitation [10, 11], which still exists in the tapered orifices. Despite the effort devoted to understanding the cavitation flow inside the nozzle, few of work focused on the string cavitation. Thus, the experimental data available for string cavitation phenomenon are lacking, and the understanding of physical processes inside it are incomplete. Chahine *et al.* [12, 13] studied the vortex-string cavitation in propellers, hydraulic turbines and hydrofoil. They represented a promising theoretical background to the string cavitation, but they have not yet been applied to nozzle flow. Andriotis *et al.* [14] investigated the string cavitation in large-scale diesel nozzles, and found the formation of string cavitation was a rather transient phenomenon. Arcoumanis *et al.* [15] observed string cavitation in real-size diesel nozzles without detail analysis. Watanabe *et al.* [16] analyzed the relationship between the vortex flow and cavitation behaviors in diesel nozzles. They found that the string cavitation correlated well with the spray formation, especially the spray cone angle.

The object of this study was to find out the laws of occurrence and development of the string cavitation at different operating conditions, and to explain the effects of string cavitating flow on spray characteristics.

Experimental set-up and test method

According to results of X-ray technique [17, 18], the cause of the various spray characteristics was the nozzle internal flow, besides the air entrainment and resistance. Due to the complicated principle and high cost of X-ray technology, it is necessary to visualize the diesel nozzle. Moreover, the flow situation in real nozzles are characterized by pressure gradients in the order of 200-300 MPa per mm through the nozzle hole, and velocity gradients in the order of 1000 m/s per mm across the nozzle hole diameter. Additionally, sizes of diesel nozzle are in the order of 0.1 mm, and the geometry structures are too complex to be processed transparently. Thus, the simplified enlarged optical diesel nozzles were studied. Schematic diagram of the nozzle flow and spray visualization system was shown in fig. 1, which was described in detail by our previous work [8]. The injector was enlarged to match the scaled-up optical nozzle tip which were derived from real injector nozzles. The testing nozzles discharging fuel into the ambient atmosphere were placed between the LED light source (100 W) and high-speed camera (FASTCAM SA-Z). By adjusting the focal plane, the images of internal flow and spray of the testing nozzles could be obtained at stable conditions with the needles fixed and various injection pressures. The framing rate was fixed at 20000 fps, that is, the interval between neighboring images was 50 μs. The fixed resolution of 1024×1024 was selected. In a typical image obtained from the experiments, the liquid phase inside the nozzle was white because the light was reflected, and the cavitation regions (vapor cavitation and non-condensable gas) were black with no light entering the camera lens. The larger the volume fraction of the gas phase was, the darker the cavitation region color was. Conversely, liquid regions same with cavitation region were shown in black in the spray zone with the similar light reflection theory.

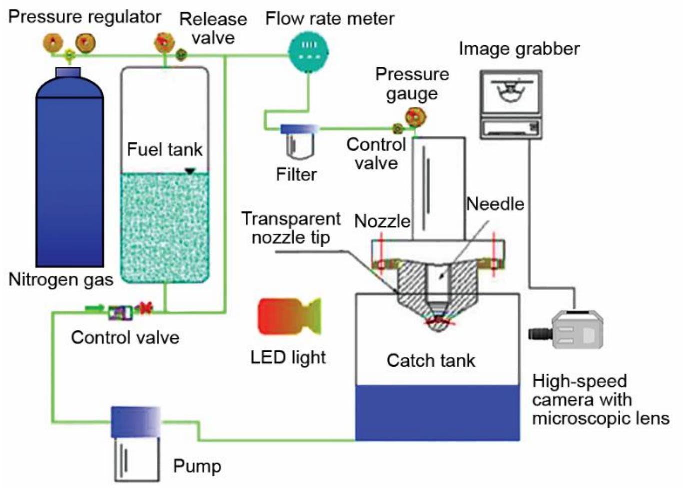

Figure 1. Schematic diagram of the visualization set-up

Previous researches showed that tapered nozzles had the high flow efficiency and were effective at suppressing geometry-induced cavitation. While there still exists string cavitation in the tapered nozzles. In this study, a nozzle with two tapered orifices was applied, the schematic diagram and the geometric structure parameters of which were shown in fig. 2 and tab. 1. The injector was enlarged based on the principles of geometric and dynamic similarity [16, 17]. The real sizes of the hole inlet and outlet are 0.2 mm and 0.18 mm, respectively, and the scaling factor is 10. Besides the principle of geometric similarity, the nozzle was designed according to the dynamic similarity criterion, that is, the cavitation number and the Reynolds number were similar to the ones of a real diesel engine injector. The scaled-up min-sac nozzle tip replicas were made by the 3-D printing and finish machining technologies. The 3-D printing technique precisely controlled the nozzle sac and orifice patterns, and the refractive index of acrylic is about 1.47 that is similar to the fuel of diesel.

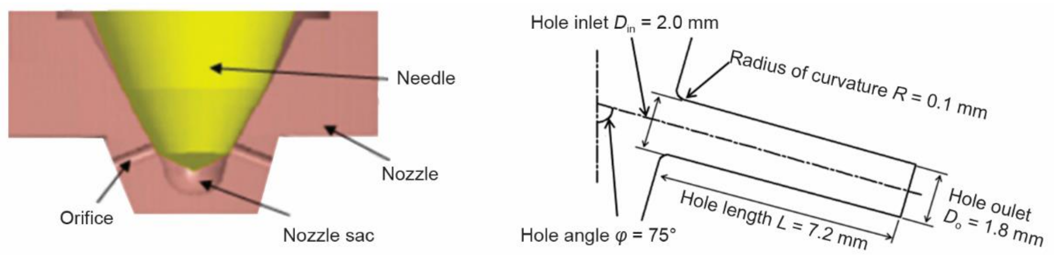

Figure 2. Schematic diagram of the tested nozzle

Table 1. Geometric structure parameters of the nozzle with two tapered holes

Hole inlet D_{in} [mm]	Hole outlet D_o [mm]	Hole length L [mm]	Radius of curvature R [mm]	Hole angle φ [°]
2.0	1.8	7.2	0.15	75

Three different needle lifts of 0.5 mm, 1.5 mm, and 3.5 mm were set to investigate effects of the needle lift on the string cavitation flow. That is, 0.05 mm, 0.15 mm, and 0.35 mm of needle lifts in the real size nozzle. The injection pressures were adjusted from 0.2 MPa to 1.6 MPa, and the fuel physical properties were shown in tab. 2.

Table 2. Physical properties of the fuel

Temperature T [K]	Working fluid	Density ρ [kgm^{-3}]	Saturated vapor pressure P_v [Pa]	Viscosity μ [mPa·s]	Surface tension σ [mNm^{-1}]
293	0# commercial diesel (China IV)	855	1280	3.4	27.19

Results and discussion

Origins of string cavitation

Optical results show that there were two different origins of the string cavitation inside the nozzle, originating either from the hole entrance or from the outlet of the hole.

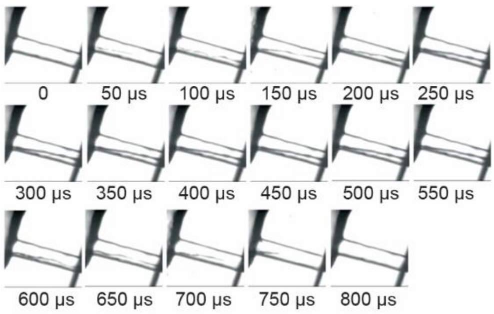

Figure 3. Evolution of the string cavitation originated from the inlet of the hole (h = 0.5 mm, P_{in} = 0.5 MPa)

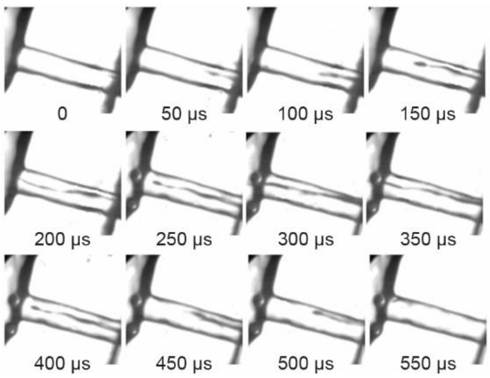

Figure 4. Evolution of the string cavitation originated from the outlet of the hole (h = 0.5 mm, P_{in} = 0.6 MPa)

Figure 3 shows a sequence of images captured with the needle lift of 0.5 mm, and injection pressure of 5 bar. In operating condition, a weak string cavitation flow was forming at the inlet bottom corner of the injection hole at the time of 50 μs, and the clear string cavitation was found running through the whole hole at 150 μs. Then, from the time of 250 μs to 550 μs, the string cavitation kept the unbroken form. After that, the string cavitation broke into shorter ones and vanished finally at 750 μs. The whole lifetime of this string cavitation was about 700 μs. The main reason for the string cavitation originated from the hole entrance was the vortices. The flow direction of the fuel would be changed drastically when the fuel flowed into the hole from the sac, which resulted in the vortex structure near the inlet of hole. Therefore, the string cavitation was a visualization form of the vortex structure.

Figure 4 shows a sequence of images captured with the needle lift of 0.5 mm, and injection pressure of 6 bar, which was a typical process that the string cavitation originated from the air suction downstream of the hole exit as well as developed to the upstream of the hole. From the appearance form and the formation mode, it can be found that downstream air entered into the nozzle orifice, and then formed the string cavitation. A thread of air was found to enter into the orifice and extended towards the upstream of the orifice along from the moment of 50 μs. Up to the time of 300 μs, the string cavitation elongated to the inlet of the orifice. Then, the string cavitation presented a gradual weakening trend and eventually disappeared. The string cavitation derived from the air outlet of the orifice reflected that there was a radial velocity of the fuel flow at the hole exit. Swirling flows inside the injector hole caused sufficient pressure drop, which made the air sucking into the orifice from the exit and then went upstream along the orifice.

Evolutions of string cavitation

Effects of the needle lift on the string cavitation

In order to elucidate the evolution of string cavitation by the needle lift, the experiments were carried out with the fixed low, middle and full needle lifts, the specific values of which are 0.5 mm, 1.5 mm, and 3.5 mm, respectively. Figure 5 illustrates the minimum injection pressure at which the string cavitation was observed at the three different fixed needle lifts. It can be seen that the critical injection pressures corresponding to the string cavitation occurrence at the three different needle lifts were different. With the increasing of the needle lift, the critical injection pressure corresponding increased since the lower needle lift was beneficial to the occurrence of string cavitation under steady states. Moreover, it can be found from fig. 5 that the string cavitation at higher needle lift was weaker than that at lower needle lift, and the lifetime of string cavitation at lower needle lift was longer. The results showed string cavitation was easier to occur and develop at lower needle lift since the scale and strength of the vortex flow in the nozzle sac were changed with the change of needle lift. In the lower needle lift, the space between the needle and the nozzle was narrow, and the swirling flow structure was formed in the nozzle sac, which caused a large vortex flow.

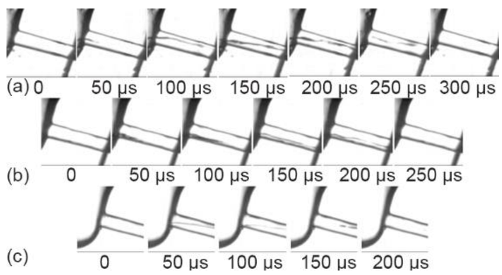

Figure 5. String cavitation formed in the injector hole at three different needle lifts; (a) low needle lift *h* = 0.5 mm, critical injection pressure P_{in} = 0.40 MPa, (b) middle needle lift *h* = 1.5 mm, critical injection pressure P_{in} = 0.6 MPa, and (c) full needle lift *h* = 3.5 mm, critical injection pressure P_{in} = 1.6 MPa

Table 3. The occurrence regularity of string cavitation under different injection pressure

Needle lift, *h* [mm]	Injection pressure P_{in} [MPa]	Occurrence frequency of string cavitation	Total duration of string cavitation [ms]
0.5	0.5	5	11
0.5	0.8	8	27.45
0.5	1.2	11	71.65

Effects of the injection pressure on the string cavitation

To investigate effects of the injection pressures on string cavitation, contrast experiments under different injection pressure of 0.5 MPa, 0.8 MPa, and 1.2 MPa were carried out at the same needle lift of 0.5 mm. The statistical results according to the three different injection pressures were shown in tab. 3. The occurrence frequency and duration of string cavitation would grow with the increasing of injection pressure. The higher injection pressure was beneficial to string cavitation occurrence and development due to the enhanced flow turbulence that strengthened the vortex flow.

Figure 6 depicts the variation trends of the occurrence frequency and the total duration of string cavitation with the increasing injection pressure. Apparently, the total duration and the occurrence frequency increased with the increasing injection pressure but the growth rates were significantly different. The occurrence of string cavitation had a lower growth rate than the string cavitation duration time. Thus, increasing the injection pressure had the positive influences on prolonging the string cavitation life time.

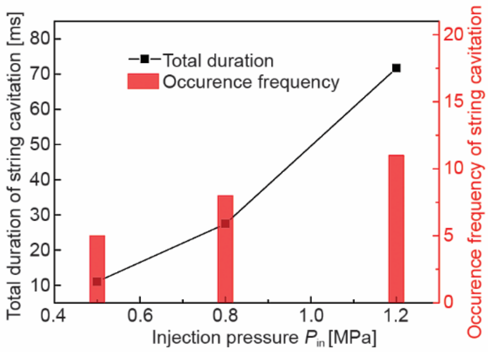

Figure 6. String cavitation occurrence frequency and the total duration variation at different injection pressure

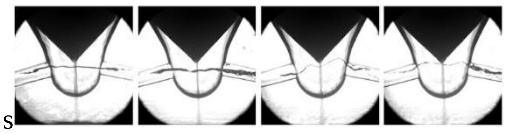

Figure 7. The string cavitation between the sac and tapered holes (P_{in} = 1.0 MPa, h = 0.5 mm)

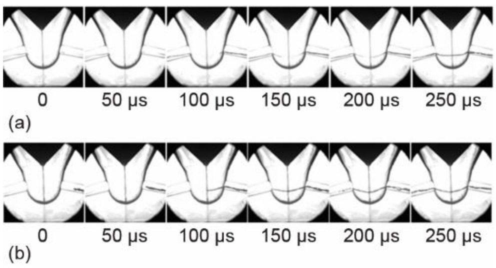

Figure 8. The formations of hole-to-hole string cavitation (P_{in} = 1.0 MPa, h = 1.5 mm); (a) string cavitation formed in both holes and connected in sac (type-A), (b) string cavitation formed in one hole and elongated to the other hole via the sac (type-B)

Effects of string cavitation on the internal flow of the nozzle and the spray

Due to the high flow efficiency and weak or even no geometry-induced cavitation, more and more tapered orifices were adopted in diesel injectors. Meanwhile, there still existed string cavitation in the tapered nozzle induced by vortex flow. However, the string cavitation had a great influence on spray cone angle, and enhanced the instabilities on atomization. The effects of string cavitation were analyzed in this section, especially the effects on the in-nozzle flow and spray cone angle.

Effects of string cavitation on the internal flow of the nozzle

String cavitation is a symbol of the vortex flow to some extent. String cavitation patterns between the sac and the two tapered orifices were presented in fig. 7. Various string cavitation structures were clearly observed since the position and intensity of the vortexes in the nozzles were transient.

Two typical formation processes of the string cavitation between hole and hole were demonstrated in fig. 8. The string cavitation occurred in the two holes firstly, then elongated to the sac and finally formed a complete string cavitation connected in the sac, which was named Type-A string cavitation, as shown in fig. 8(a). The evolution process of type-B was shown in fig. 8(b) that the string cavitation only appeared in one hole initially, and then extended to the other hole *via* the sac due to the air suction, fig. 5.

Moreover, experiments at different injection pressures of 0.7 MPa, 1 MPa, and 1.5 MPa were carried out with the same needle lift of 1.5 mm to study the relationship between the occurrences of the two types of string cavitation and the injection pressure. Results were presented in fig. 9, where the occurrences of the two types (type-A and type-B) string cavitation showed the similar trend under the different injection pressures. The higher injection pressures the larger occurrence frequencies of string cavitation. However, the type-A string cavitation was not observed under the injection pressure of 0.7 MPa when the type-B string cavitation had appeared, but which was easier to be found at the higher injection pressures, such as 1.0 MPa and 1.5 MPa.

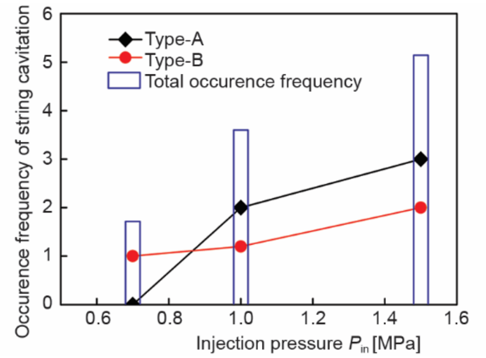

Figure 9. Occurrence frequencies of different string cavitation formation types under different injection pressures (*h* = 1.5 mm)

Besides the interacts between the orifices, the string cavitation also triggered the geometry-induced cavitation, as shown in fig. 10. Generally, the geometry-induced cavitation would not occur under the injection pressure of 1.0 MPa in the tested tapered nozzle at the needle lift of 0.5 mm, fig. 10(a). However, it can be found from fig. 10(b) that there was geometry-induced cavitation when string cavitation existed, and which would vanish when the string cavitation disappeared, which indicated that the geometry-induced cavitation occurred here was dependent on the string cavitation. On one hand, the pressure distribution was changed by the string cavitation. And on the other hand, more air nuclei were introduced into the orifices. However, the geometry-induced cavitation caused by the string cavitation only was near the inlet of orifice.

Figure 10. The geometry-induced cavitation caused by string cavitation (P_{in} = 1.0 MPa, *h* = 0.5 mm); (a) no *geometry-induced* **cavitation and** *string cavitation*, **(b)** *geometry-induced* **cavitation appeared with the** *string cavitation*

Effects of string cavitation on the spray cone angle

Figure 11 demonstrates the spray cone angle and string cavitation extension length in the orifice under the injection pressure being 0.8 MPa with needle lift being 0.5 mm. The

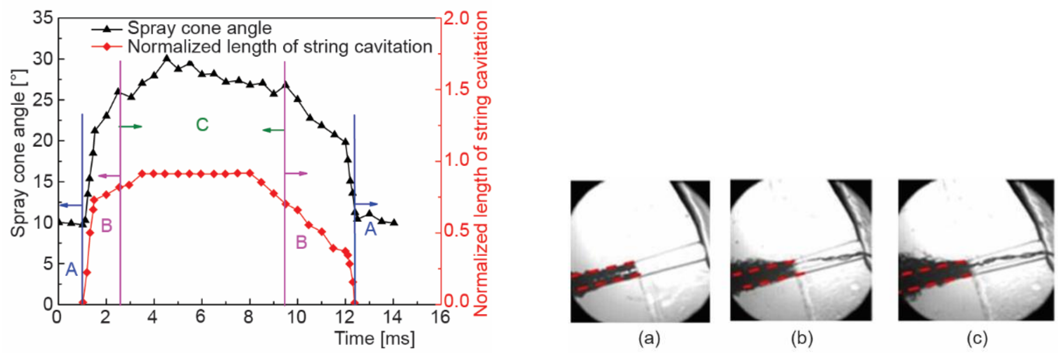

Figure 11. The relationship between the string cavitation and spray cone angle; (a) there is no string cavitation, (b) near the hole exit string cavitation is weak, and (c) strong string cavitation extends to the hole exit

normalized length of string cavitation is the length of string cavitation region to the length of orifice. The various spray cone angles were consistently observed. Evolution of the spray cone angle was divided into A, B, and C phases. At the moments of A phase, there was no string cavitation inside the orifice, the spray cone angles were stable at about 10°, as shown in fig. 11(a). String cavitation occurred inside the orifice and extended to near exit of the hole in the phase of B, where the spray cone angles were increased or decreased with the length of string cavitation, fig. 11(b). The string cavitation was weak near the hole exit. During the C phase, the string cavitation extended out the nozzle orifice and the spray conde angles oscillated between 25° and 30°, fig. 11(c). These results revealed that the occurrence of string cavitation could cause a huge upsurge in the spray cone angle since the string cavitation intensified the strength of radial direction velocity in nozzle orifice, and the strong radial direction velocity increased the spray cone angle.

Conclusions

Optical results of the string cavitating flow inside the tapered diesel injector nozzles were presented, providing more insights into the details of the characteristics and effects of the string cavitation. Based on the present study, the following conclusions have been drawn:

- There were two origins of the string cavitation. One was formed at the inlet of the injection orifice and elongating to the orifice outlet because of the vortexes. The other one was originated from orifice outlet to inlet due to the contribution of air suction.
- The critical injection pressures of string cavitation were increased with the increasing of the needle lift. The string cavitation at high needle lift was weak and its lifetime was short. The lower needle lift was beneficial to the occurrence and development of string cavitation.
- There were two typical formation processes of the hole-hole string cavitation. Type-A was that the string cavitation occurred in the two holes firstly, then elongated to the sac and finally formed a complete string cavitation through the sac. The string cavitation only appeared in one hole initially, and then elongated to the other hole via the sac in the type-B string cavitation.
- The string cavitation triggered the geometry-induced cavitation, and the string cavitation sharply increased the spray cone angles.

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