Visualization of Internal Flow and Spray Formation with Real Size Diesel Nozzle

Tomohiro Hayashi[*1], Masayuki Suzuki[2], Masato Ikemoto[3]
1: NIPPON SOKEN, INC., Nishio, Aichi Japan
2: DENSO CORPORATION, Kariya, Aichi Japan
3: TOYOTA MOTOR CORPORATION, Susono, Shizuoka Japan

Abstract

The internal flow of a diesel mini-sac (MS) and valve-covered orifice (VCO) nozzle and its spray formation have been investigated by flow visualization with a real-size transparent nozzle. The mechanism of cavitation generation in the nozzle has been studied by focusing on the transient flow pattern in the sac with micro PIV and numerical simulation. String-type and film-type cavitations are separately observed in the nozzle hole during the injection stage. In the case of low needle-lift for MS nozzle, the string-type cavitation is generated by a secondary flow in the hole and stretched to the other hole through the vortex core in the sac. With the increase of needle-lift, film-type cavitation that formed at the hole inlet edge becomes dominant. This transition of the cavitation type is related to the change of the flow pattern in the nozzle sac. On the other hand, only the film-type cavitation was observed in the VCO nozzle. Through analyzing the frequency of cavitation generation and spray fluctuation, it is also evident that with the increase of string-type cavitation, spray cone angle tends to be wide.

Introduction

In order to achieve low fuel consumption and clean emission of automobiles, it is essential to optimize the engine combustion. The performance of diesel engine is largely affected by process of fuel atomization and distribution in the combustion chamber. The principal characteristics of fuel spray that govern the diesel combustion are droplet size, spray tip penetration, spray cone angle and their fluctuation during the single injection and shot-to-shot variation. For the modern diesel engine, one of the key components is a common rail fuel injection system. Common rail systems enable the increase of combustion efficiency and reduce smoke and combustion noise by multiple injection of the highly pressurized fuel by quick-response injector. Recently, many studies have focused on the internal flow in the injector nozzle and its spray formation. They indicate that the spray characteristics are markedly influenced by cavitation generated in the nozzle hole. However, it is difficult to directly observe the extremely high speed flow in the minute space between the seat and hole of the diesel nozzle. In order to settle this issue, several studies have attempted to replicate and visualize the flow characteristics with enlarged transparent nozzle [1,2,3,4]. These flow visualizations are conducted by adjusting the Reynolds number in the large-scale nozzle to that of the real-size nozzle with alternative fluid, thereby allowing researchers to perform more detailed analysis. However, this technique is not able to precisely reproduce those transient characteristics that occur in the injection duration, as well as the spray that is injected from an actual nozzle hole. These days, there have been some efforts made for the flow visualization with real-size nozzle [5,6]. However, the understanding of phenomena inside the nozzle is still limited.

The purpose of this study is to find the fundamental relationship between internal flow and spray formation of the nozzle as feedback for the nozzle design. We established the flow visualization method in the real-size nozzle and investigated the relationship between the transient nozzle internal flow, cavitation, and spray formation. A mini-sac (MS) nozzle and valve-covered orifice (VCO) nozzle were surveyed to analyze the influence of the nozzle design toward the internal flow and spray characteristics. We also tried identifying the contributing factors that let to the occurrence of cavitation through examining the flow in the nozzle sac and hole by micro PIV and computational fluid dynamics (CFD) analysis.

Experimental Setup

Transparent nozzle

Figure 1 shows the transparent nozzle used in the study. The tip of an actual injector nozzle was modified to provide optical access. The transparent nozzle is made of acrylic resin, which possesses a refractive index that is similar to that of the diesel fuel. In order to evaluate the internal flow and cavitation generated in the actual nozzle, the geometry of the sac and hole of the transparent portion are made to be the same as the original nozzle. Also, the inlet roundness of the hole and cone angle have been designed to match those of the actual nozzle.

* TOMOHIRO_HAYASHI@soken1.denso.co.jp

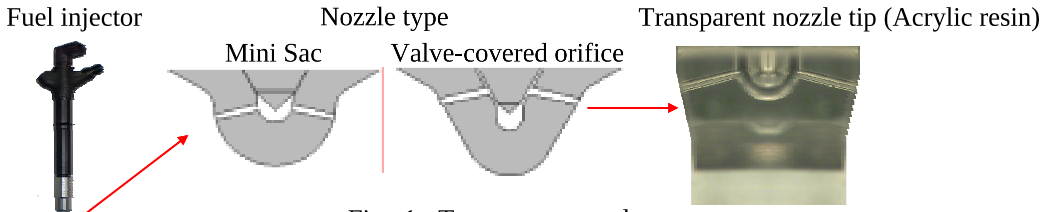


Fig. 1 Transparent nozzle

Visualization system and conditions

Figure 2 shows the visualization system that was used for the observation of internal flow and cavitation in the transparent nozzle. A shadowgraph technique has been introduced to observe cavitation in the nozzle and the spray formation process during fuel injection. A high-speed camera (Photron FASTCAM SA1.1 resolution is 320x128 pixels, image capture speed is 0.1Mfps) and a metal-halide lamp were used to obtain the cavitation and spray images. The velocity profile of internal flow in the nozzle is measured by micro PIV. The tracer particle (average diameter is 10μm and relative density is 2.0g/cm^3) is added to the fuel. Continuous image was captured by high-speed camera (Shimadzu HPV-2A resolution is 312x260 pixels, image capture speed is 1Mfps) and a strobe light (Sugawara ESD-VF2M-U2). In order to perform a series of investigation under an injection environment that approximates the actual engine condition, visualization was implemented in the pressure chamber filled with argon gas (0.88MPa).

Figure 3 shows a typical captured image of the flow in the transparent nozzle. Since the refractive index of transparent nozzle made of acrylic resin (1.49) is closed to diesel fuel (1.46), light is able to permeate the interior of the nozzle sac filled with fuel. On the other hand, cavitation (gaseous phase) can be observed as a dark shadow since the refractive index of the gaseous phase is different from that of acrylic resin.

In this study, a Denso third generation piezo injector was used to control the nozzle needle. Table 1 and 2 indicate the nozzle specifications and the test conditions. The Reynolds number shown in Table 2 is defined as Re = du/ν, where d is the representative length (nozzle hole diameter). The cavitation number is defined as CN = $(P_a-P_v)/(P_{inj}-P_a)$.

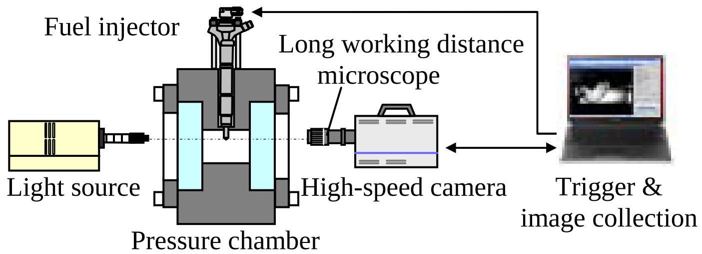


Fig. 2 Experimental apparatus

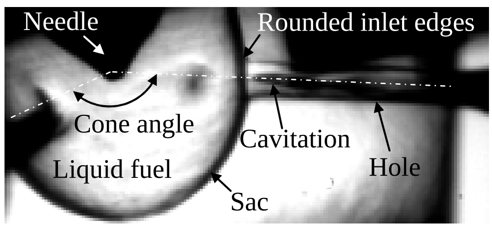


Fig. 3 Example of a flow in the nozzle

Table 1 Specifications of the Test Nozzle

Nozzle type			MS		VCO
Hole number	n	[-]	3	6	3
Hole diameter	d	[mm]	φ0.14	←	←
Hole length	L	[mm]	0.8	←	1.05
Inlet roundness of hole	R	[mm]	0.033	←	←
Cone angle	α	[deg.]	155	←	←

Table 2 Experimental conditions

Vapor pressure	P_v	[MPa]	4.0	
Ambient temperature	T_a	[K]	293	
Ambient pressure	P_a	[MPa]	1.0 (Ar gas: ρ=15kg/m^3)	
Injection pressure	P_{inj}	[MPa]	40	50
Reynolds number	Re	[-]	10630	11910
Cavitation number	CN	[-]	0.025	0.020

Numerical simulation method

The commercial CFD code FIRE ver. 2008 (AVL) was used for the calculation of the nozzle internal flow. Figure 4 shows the computational grid of the 3-hole MS and VCO nozzle for the simulation. By taking into account the geometric periodicity, only one third of the whole internal flow area of the nozzle was chosen as a computational domain. The measured transient needle-lift and inlet pressure are applied for the computational model. The RANS scheme with standard K-ε model is introduced to describe the turbulent flow in the nozzle and spray chamber. The assumed fluid is composed of three constituents, i.e., liquid / gas phase fuel and air. The behaviors of cavitation bubble is expressed by the linearized Rayleigh model.

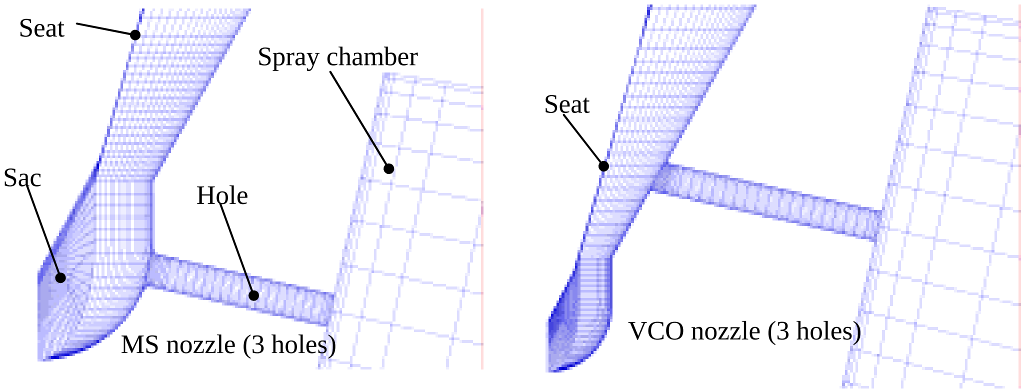


Fig. 4 Computational grid for the simulation in the nozzle flow

Results and Discussion

Visualization of cavitation in the nozzle

Figure 5 shows the visualization result of cavitation in the MS and VCO nozzle. At the outset of the injection test, the fuel in the sac and hole is purged to approximate the injection environment of an actual engine. As mentioned in the previous studies [7,8,9], the string cavitation is observed within the MS nozzle hole. The coalescence of the string cavitation between separate nozzle holes was captured during the initial, low needle-lift state of injection. When the nozzle needle is fully lifted (0.90ms after start of injection; ASOI), the film-type cavitation (separate from the aforementioned string cavitation) is generated on the nozzle hole inlet. Along with increase of the pressure in the sac, the string cavitation in the nozzle sac vanished. In comparison, the film-type cavitation occurred at a great frequency in the hole of the VCO nozzle. The film-type cavitation in the VCO nozzle hole grows toward the nozzle hole outlet. By examining the images yield at the end of injection (2.50ms ASOI), the intrusion of bubbles into the nozzle sac and hole was observed with the MS nozzle. On the other hand, the intrusion of bubbles was only observed in the nozzle hole of the VCO nozzle, as the nozzle hole inlet is covered by a nozzle needle.

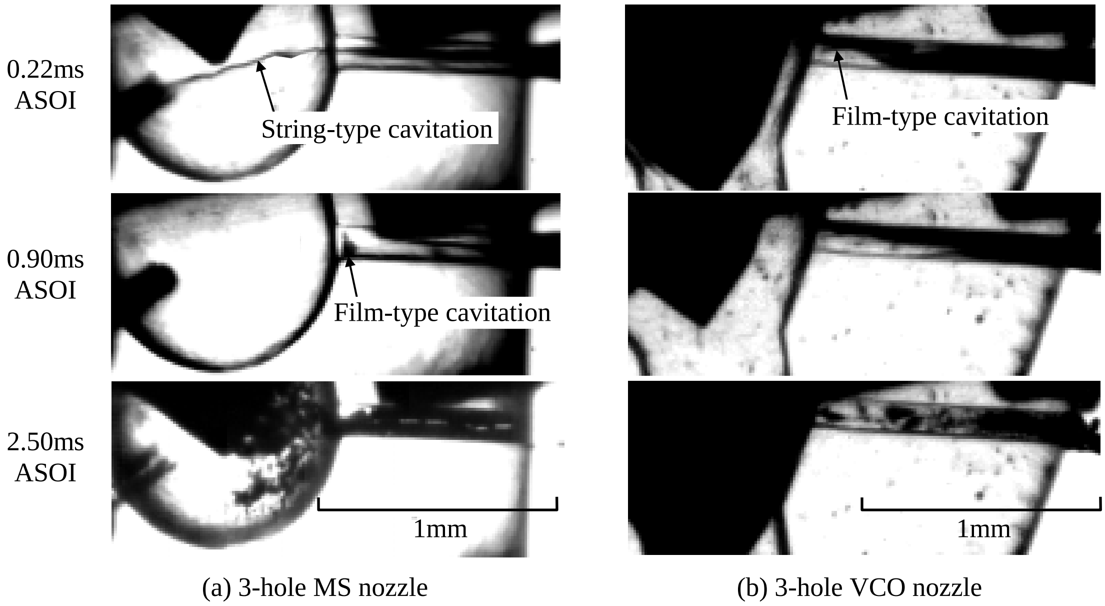


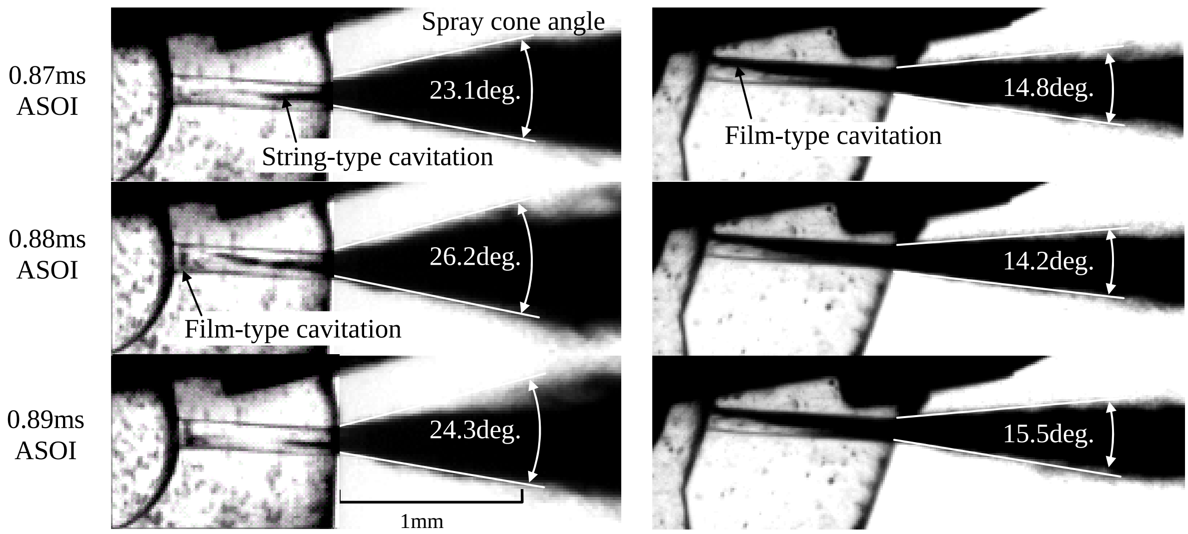
Fig. 5 Transient characteristics of cavitation in the nozzle (P_{inj}=40MPa, t_{inj}=1.0ms)

Relationship between cavitation and spray

In order to assess the relationship between cavitation and spray formation, we conducted a simultaneous observation of the cavitation and spray. Figure 6 shows a chronological representation of the nozzle internal flow and spray formation. By focusing on the behavior of the cavitation and spray cone angle, a tendency can be seen for the MS nozzle which is, that the area fluctuation of nozzle hole covered by string cavitation synchronizes the spray cone angle. The spray cone angle is calculated by using the straight-line distance between the spray width measured 1mm away from the nozzle hole outlet and the nozzle hole outlet itself. On the other hand, there is no significant variation in the length of cavitation. Regarding the VCO nozzle, cavitation that occurs at the nozzle hole inlet growing outward the nozzle outlet indicates little change, and the variation of the spray cone angle was also small. Additionally, the spray cone angle of VCO nozzle was narrower than that of the MS nozzle. Based on these result, as seen in Figure 7, it can be assumed that string cavitation has a great influence on spray formation compared to the effect of the cavitation that roots in flow separation.

Figure 8 and 9 show the measured cavitation length, string cavitation thickness, and spray cone angle at the nozzle hole outlet. The length of cavitation is measured according to its change rate against the nozzle hole length. For string cavitation, the cavitation thickness is a non-dimensional number that was calculated as a rate of thickness to the hole diameter (average value in the hole region that diameter is d) at the hole outlet. Hence, there is a trend that the spray cone angle of MS nozzle depends on the thickness of non-dimensionalized string cavitation. The spray cone angle would increase as the thickness of the string cavitation increases. This trait is identical to the results that are shown in Figure 5. There it is also revealed that the string cavitation is remarkable during the initial and final injection states, i.e., low needle-lift. The thickness of string cavitation is reduced with the increase of sac pressure for high needle-lift state (0.8 to 1.8ms ASOI). Although this trend can be seen also with the VCO nozzle, the cavitation on the nozzle hole inlet plays a more dominant role rather than the string cavitation, and the spray cone angle is stable for a longer duration of time.

Based on the aforementioned results and discussion, it is summarized that the spray formation is greatly influenced by string cavitation. In particular, string cavitation is a root cause of spray fluctuation and variation for the MS nozzle, in which there is a remarkable string cavitation that changes its thickness with increase of the needle-lift.



(a) 3-hole MS nozzle (b) 3-hole VCO nozzle

Fig. 6 Transient characteristics of cavitation and spray close to the nozzle hole outlet (P_{inj}=50MPa, t_{inj}=1.0ms)

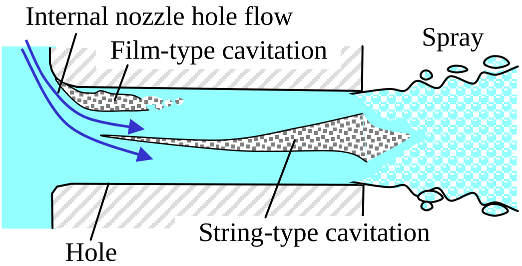


Fig. 7 Schematic of flow and cavitation in the nozzle hole

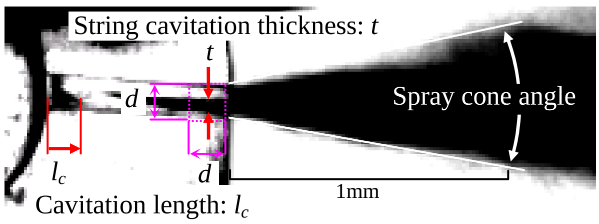
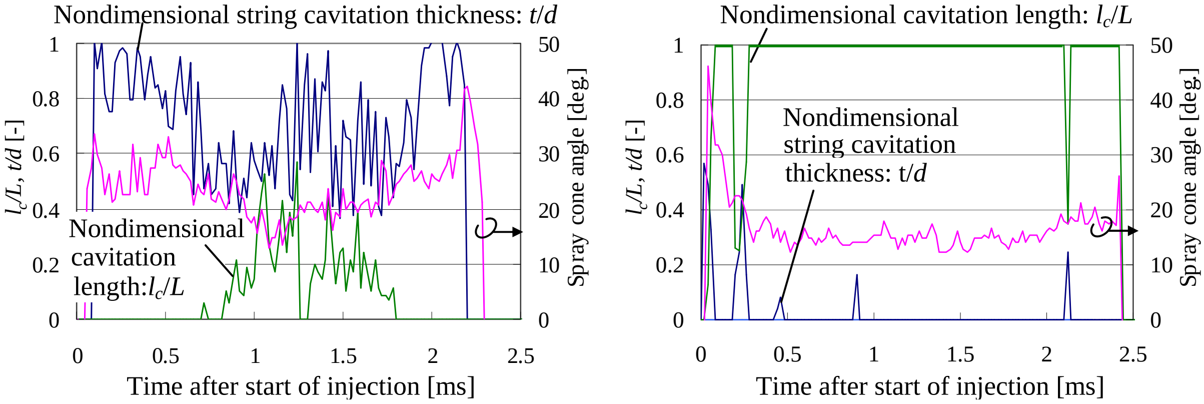


Fig. 8 Definition of cavitation profile and spray cone angle



(a) 3-hole MS nozzle (b) 3-hole VCO nozzle

Fig. 9 Cavitation characteristics and spray cone angle (P_{inj}=50MPa, t_{inj}=1.0ms)

Generation mechanism of string cavitation

In order to investigate the mechanism of the string cavitation generation, we obtained a bottom view of the flow in the MS nozzle as shown in Figure 10. The image of the string cavitation was shot using scattering light from the side of the nozzle. By focusing on the string cavitation occurring near the nozzle hole inlet, it is evident that 1 or 2 instant string cavitations exist and are connected together. Figure 6 indicates that the string cavitation is generated and developed near the hole axis. From these characteristics, it is supposed that there is a low pressure region near the hole center, and this is the generation source of the string cavitation.

In addition, we assessed the factor of string cavitation stretch and coalescence toward the other nozzle hole through the sac by flow visualization in the sac. Figure 11 shows the obtained velocity profile in the MS nozzle by micro PIV. At the timing that a string cavitation is stretched and connected to the other hole (0.3ms ASOI), there is a remarkable vortex structure in the sac flow. The vortex core can be seen on the extension of nozzle hole axis. From these evidences, it can be assumed that the variation of string cavitation thickness that related to the nozzle needle-lift is caused by the transition of the flow pattern in the sac with change of needle-lift.

Figure 12 shows the computational result of the flow in the MS and VCO nozzle. Regarding the MS nozzle, the stream line picture ensures that there is a spiral flow and low pressure region in the nozzle hole at low needle-lift state. In addition, both stream line and velocity profile indicate a vortex structure in the sac that is also measured in the actual nozzle as seen in Figure 11. On the other hand, the vortex structure does not exist in close proximity of the nozzle hole inlet for VCO nozzle whereas the marked flow separation is observed in the hole inlet.

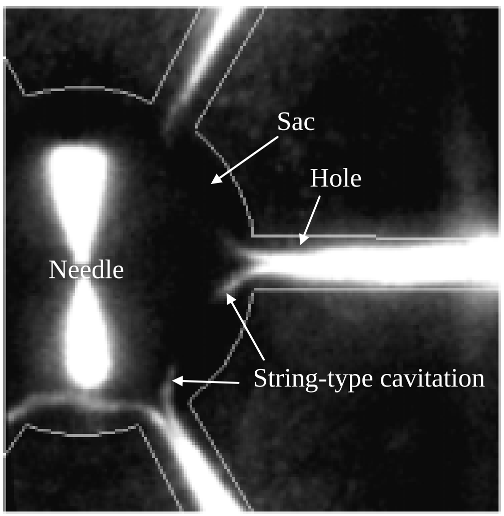
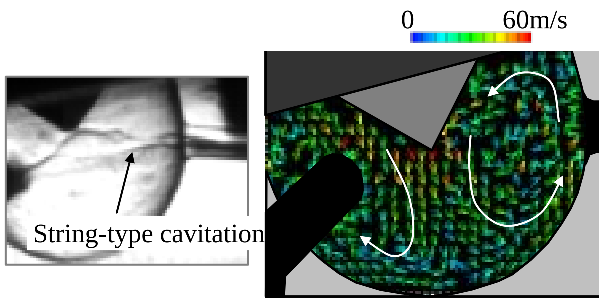
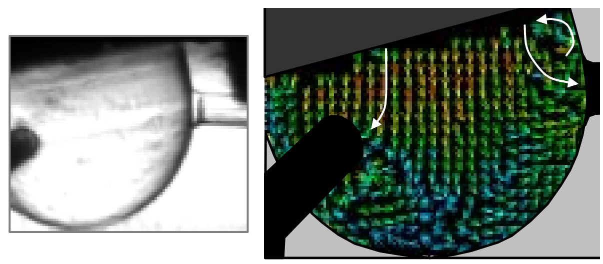


Fig. 10 Bottom view image of internal flow in 6-hole MS nozzle (P_{inj}=40MPa, t_{inj}=1.0ms, 0.2ms ASOI)



(a) 0.30ms ASOI



(b) 1.00ms ASOI

Fig. 11 Internal flow in 3-hole MS nozzle by PIV (P_{inj}=50MPa, t_{inj}=1.0ms)

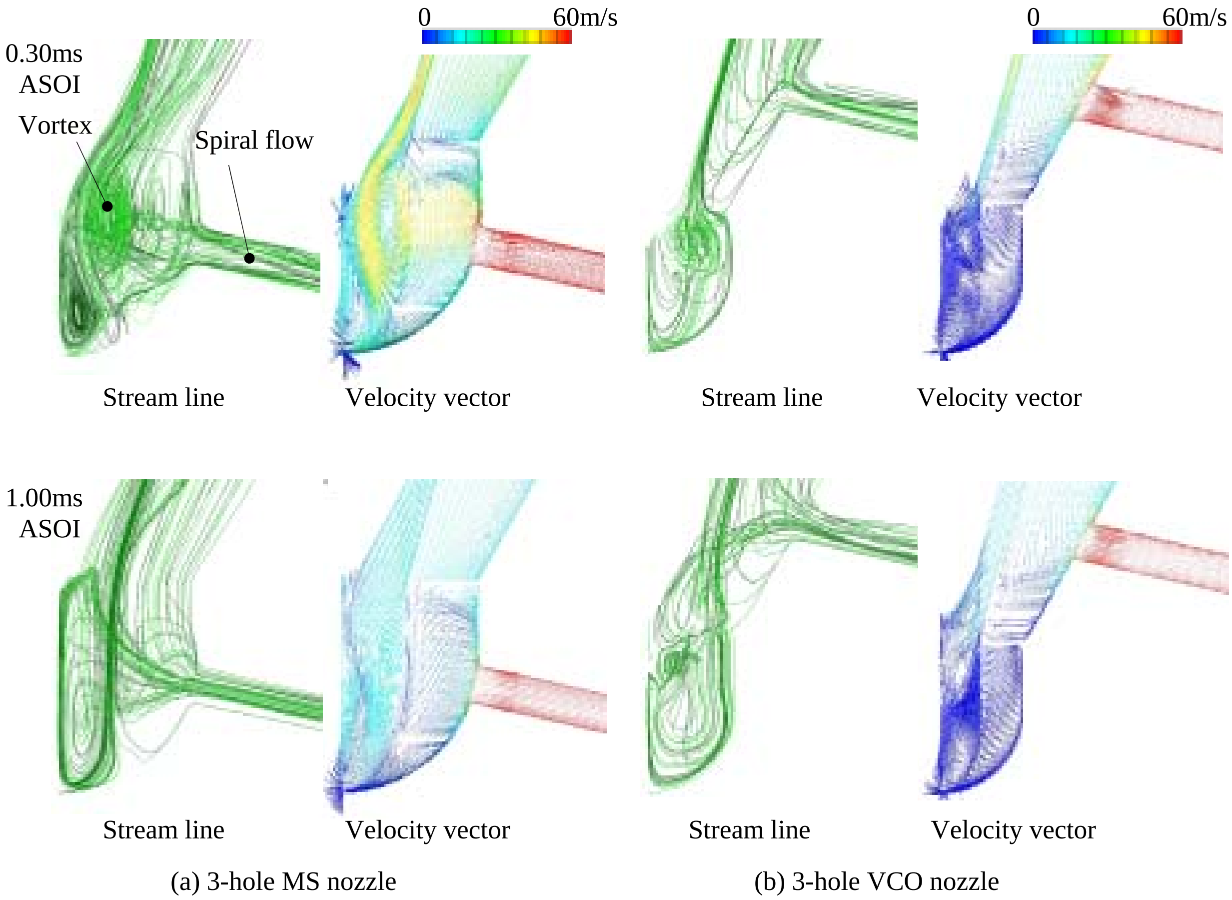


Fig. 12 Stream line and velocity vector in the nozzle (CFD)
(P_{inj}=50MPa, t_{inj}=1.0ms)

Conclusion

The relation between the internal flow, cavitation behavior and spray formation of real-size diesel nozzle is analyzed by both experimental measurement and numerical simulation. In order to investigate the transient internal flow in the nozzle and spray formation, we developed a flow visualization technique by high-speed camera and micro PIV with a transparent nozzle. The following conclusions were drawn:

(1) Under the tested injection pressure condition (50 MPa), the string cavitation was found in the MS nozzle. On the other hand, the film-type cavitation is dominant in the VCO nozzle, which results from the flow separation at the nozzle hole inlet.

(2) There is a correlation between the spray cone angle near the nozzle hole outlet and the thickness of string cavitation. Since a large amount of string cavitation in MS nozzle occurs at such a great frequency, the spray cone angle is larger than that of the VCO nozzle.

(3) The string cavitation in the MS nozzle hole is caused by spiral secondary flow. The generated string cavitation is stretched to the other hole through the vortex core in the sac.

(4) The transition of the vortex structure in the sac induces the fluctuation of the thickness of string cavitation in the hole and spray cone angle. This is vital to suppress vortex formation in the sac and stabilize the fuel injection of the nozzle.

Based on the knowledge above, the authors are aiming to propose a new nozzle design that would help achieve an ever higher injection precision.

References

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