Visualization Analysis of Relationship between Vortex Flow and Cavitation behavior in Diesel Nozzle *

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In diesel engines for passenger cars, the spray and combustion characteristics are one of the important factors for determining the exhaust and engine performances. These characteristics are affected by the internal flow, the film-type and string-type cavitations in the diesel nozzle. Specifically, the string-type cavitation correlates well with the spray cone angle and the string-type cavitation behavior destabilizes the spray formation and combustion. The string-type cavitation is influenced by the vortex flow in the nozzle sac. Therefore, it is important to clarify the effect of nozzle and needle shapes on the vortex flow for further development of the diesel injector. This study investigates the effect of needle tip shape on a vortex flow, string-type cavitation and the spray characteristics. This was realized by comparison of the three needle shapes which were chosen in order to control the vortex flow in nozzle sac. A real-size transparent nozzle technique was used to investigate the relationship between the vortex flow and cavitation behavior in the diesel nozzle. This technique allows a spray characteristic to be observed concurrently with the inner flow as well. In addition, the visualized vortex flow was analyzed in detail by the micro PIV method and computational fluid dynamics (CFD).

Key words :
Diesel Engine, Fuel Injection, Cavitation, Vortex Flow and Flow Visualization

1. INTRODUCTION

Clean and high efficiency combustion is required to achieve the fuel consumption and exhaust gas regulations in the future. In the diesel engines, common rail fuel injection system has been widely employed for achieving high efficiency and low emission. In the common rail system, injector is an important part in determining the engine performance and exhaust gas. The fuel spray injected from the nozzle hole is momentarily burned in-cylinder. Therefore combustion of the diesel engine is largely affected by the 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 variation during a single injection. These characteristics are largely affected by the internal flow of the nozzle. Therefore, many studies have focused on internal flow and

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spray formations. These studies have indicated that the spray characteristics are markedly influenced by cavitation generated in the nozzle hole. However, direct observation between the seat and nozzle hole of the diesel is difficult due to the high-speed flow in a narrow space. In order to resolve this issue, some studies have attempted to replicate and visualize the flow characteristics with enlarged transparent nozzles[1)2)3)]. 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. Recently, there have been some efforts to make flow visualization with real-size nozzles to clarify the relationship between the flow characteristics and combustion[4)5)6)7)]. By this technique, a few studies have defined that the variation of the spray cone angle is caused by an unstable string-type cavitation behavior during fuel injection[8)]. As a result, it is important in further development of the nozzles that a one of methods for controlling the string-type cavitation are studied.

The string-type cavitation is influenced by the flow velocity in the nozzle hole and the vortex flow in the nozzle sac of which scale and strength is changed with needle-lift. In order to control the spray characteristics, previous studies have reported the string-type cavitation in the nozzle hole is controlled by nozzle geometries such as the inlet roundness, conical shape factor of the injection hole and shape of the nozzle sac[9)10)]. On the other hand, effect of the vortex flow in the sac, the string-type cavitation and spray characteristics have not been elucidated clearly. Moreover, a method of controlling the vortex flow has not also been clarified yet. Only a few studies have investigated the vortex flow in the sac. Internal flow of mini-sac (MS) nozzle concerning the needle-lift was reported as follows[11)]:

•In the low needle-lift, a large vortex flow is generated by the swirling flow structure in the nozzle sac, which originates from the attached flow on the tip of the needle surface.

•In high needle-lift, the vortex flow disappears or downscales in the nozzle sac.

These results indicate that the attached flow on the needle surface has an important role in the formation of the vortex flow in low needle-lift. Thus, optimization for flow channel geometry by the needle shape is one method to control the vortex flow in the nozzle under the low needle-lift.

This study investigates the effect of needle tip shape on a vortex flow, string-type cavitation and the spray characteristics. This was realized by comparison of the three needle shapes which were chosen in order to control the vortex flow in nozzle sac. A real-size transparent nozzle technique was used to investigate the relationship between the vortex flow and cavitation behavior in the diesel nozzle. This technique allows a spray characteristic to be observed concurrently with the inner flow as well. In addition, the visualized vortex flow was analyzed in detail by the micro PIV method and computational fluid dynamics (CFD).

2. EXPERIMENTAL APPARATUS

2.1 Needle geometries

Fig. 1 shows the internal flow of the common type MS nozzles which were presented in the past study[8)11)]. As mentioned previously, the velocity vector shows that large vortex flow form in the nozzle sac. In order to investigate the correlation between the vortex flow and the string-type cavitation, the scale and strength of the vortex flow was controlled by an angle of the needle tip α was changed.

Fig. 2 shows needle geometries in this experiment. These needles have different angle of the needle tip (α=90 degree, 70 degree and 30 degree). In Fig. 2 (a), the needle with the angle α=90 degree is the common type in the MS nozzles. The needle with the angle α=70 degree, presented in Fig. 2 (b), could cause smaller and weaker vortex flow than α=90 degree. The needle with the angle α=30 degree eliminated the space of forming the vortex in the sac so that the vortex flow in the sac could disappear.

However, sac volume of the nozzle was changed by a geometric restriction, and so the spray formation might be influenced by raising the sac pressure.

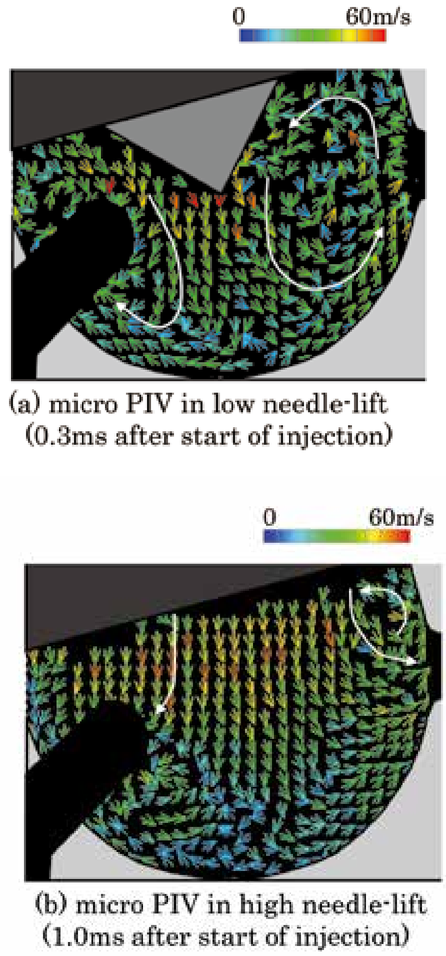

Fig. 1 Internal flow of the MS nozzle[8)11)]
(P_{inj}=50MPa, t_{inj}=1.0ms)

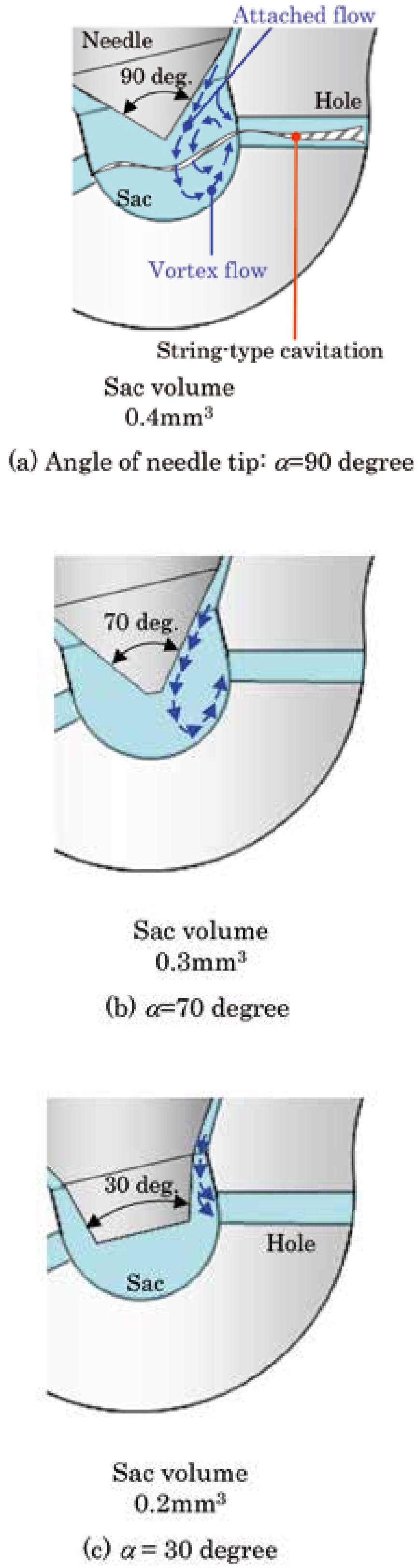

Fig. 2 Needle geometry in the experiment

2.2 Transparent nozzle

The transparent nozzle, as shown in Fig. 3, is made of acrylic resin which has a refractive index similar to that of the diesel fuel. In order to evaluate the internal flow and cavitation generated in the actual MS nozzle, geometry of the sac and hole of the transparent portion is made to be the same as the original nozzle.

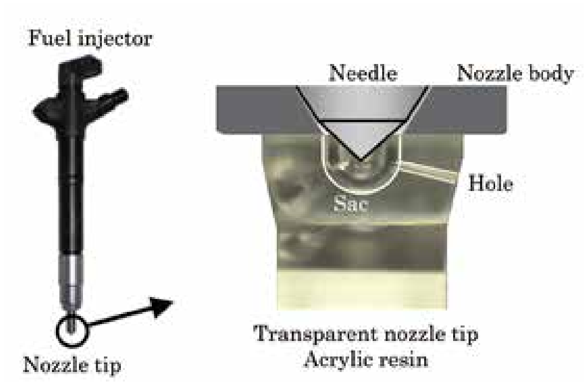

Fig. 3 Optically visible MS nozzle

2.3 Visualization system and test conditions

Fig. 4 shows the visualization system that was used for the observation of internal flow and cavitation in the transparent nozzle. A shadowgraph technique was introduced to observe cavitation in the nozzle and the spray formation process during fuel injection. Two types of high-speed camera were used for visualization. One was Photron FASTCAM SA1.1 (resolution: 320*128 pixels, frame rate: 0.1Mfps) for obtaining the cavitation and spray combustion images with a metal-halide lamp. Another one was Shimadzu HPV-2A (resolution: 312*260 pixels, frame rate: 1Mfps) with a strobe light, (Sugawara ESD-VF2M-U2) for capturing a detailed visualization of the nozzle and micro-PIV method. In the micro-PIV method, the tracer particle (average diameter is 10μm and relative density is 2.0g/cm^3) is added to the fuel. In order to perform a series of investigation under an injection environment that approximates the high density condition, pressure chamber was used to create atmosphere of density: 15kg/m^3. The pressure chamber was filled with argon gas which is an inert gas. Fig. 5 (a) shows a typical captured image of the internal nozzle and fuel spray. Since the refractive index of transparent nozzle made of acrylic resin (1.49) is close to diesel fuel (1.46),

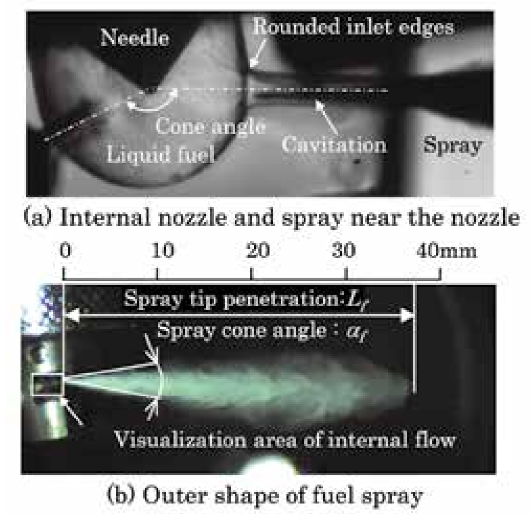

Fig. 5 Example of the visualization images

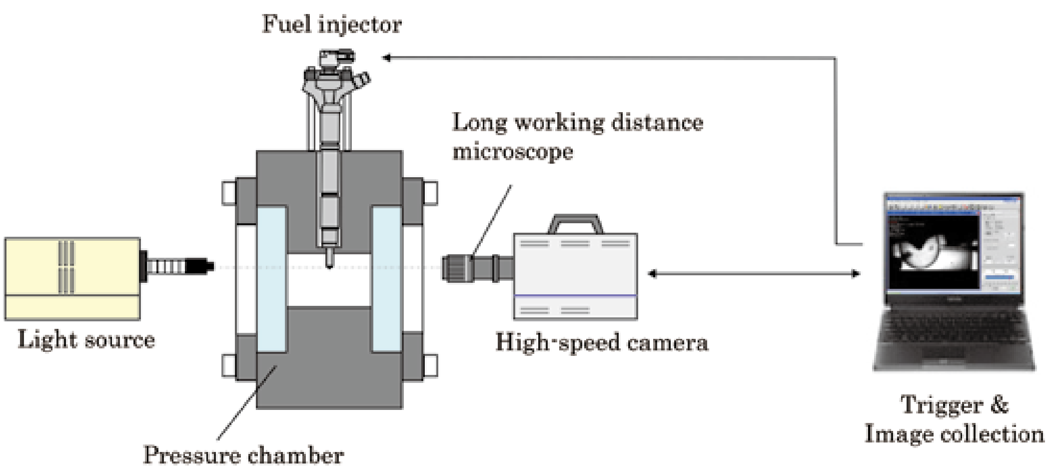

Fig. 4 Experimental apparatus

Table 1 Specification of test nozzle

Hole number	n [-]	3
Hole diameter	d [mm]	ϕ0.14
Hole length	L [mm]	0.8
Inlet roundness of hole	R [mm]	0.033
Cone angle	a [deg.]	155

Table 2 Test conditions

Ambient temperature	T_a [K]	293
Ambient pressure	P_a [MPa]	1.0 (Ar gas)
Ambient density	ρ [kg/m³]	15
Vapor pressure	P_v [MPa]	4.0
Injection pressure	P_{inj} [MPa]	50
Reynolds number	Re [-]	11914
Cavitation number	CN [-]	0.020

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. Fig. 5 (b) shows the evaluated spray cone angle and spray tip penetration. The profile of the fuel spray, which was visualized by Mie-scattered light using metal-halide lamp, can be observed as a white mist. The spray cone angle was calculated based on the straight-line distance between the spray width measured 10mm away from the nozzle hole outlet and the nozzle hole outlet itself.

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

2.4 Numerical simulation method

The commercial CFD code FIRE ver. 2008 (AVL) was used for the calculation of the nozzle internal flow. Fig. 6 shows the computational grid of the 3-hole MS 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 cavitation bubble behavior is simulated by the linearized Rayleigh model.

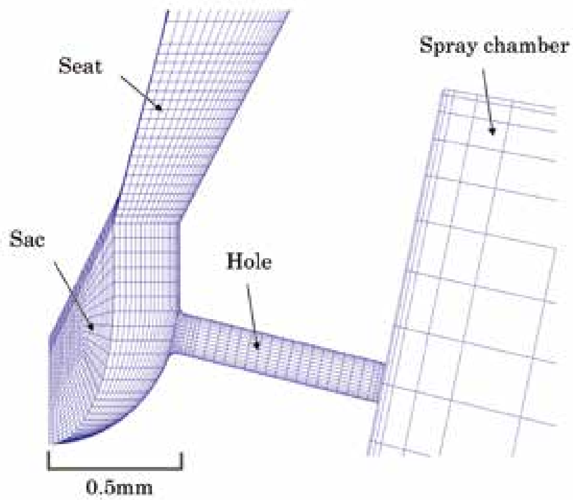

Fig. 6 Computational grid for the simulation of the nozzle flow

3. RESULTS AND DISCUSSION

3.1 Visualization of the vortex flow behavior

In order to elucidate the changing of the vortex flow by the needle geometries, the internal flow was visualized and analyzed by micro-PIV and CFD. Fig. 7 (a) shows the velocity vectors in the nozzle sac by micro-PIV and Fig. 7 (b) shows the velocity vector and stream line by CFD at 0.2ms after start of injection (ASOI) when the needle-lift was low. In nozzle with α=90 degree needle, the large vortex was formed in the sac. Then, in the nozzle with α=70 degree needle, the vortex scale was smaller than the nozzle with α=90 degree needle, because the attached flow on the needle surface flowed near the nozzle hole and the fuel flow did not path at the bottom of the sac. Moreover, the low speed flow in the vortex near the nozzle hole, presented in micro-PIV and CFD, suggests that the vortex in the nozzle sac was weak in α=70 degree. Finally, in the nozzle with α=30 degree needle, the vortex flow in the sac did not exist near the nozzle hole. The fuel in the sac was observed to directly flow into nozzle hole.

These results show that the vortex flow near the nozzle hole in the sac was suppressed by setting small angle of the needle tip. In addition, the internal flow in the sac directly streamed into the injection hole.

3.2 Relationship between the vortex flow and string-type cavitation behavior

Relationship between the vortex flow and string-type cavitation behavior was investigated. Fig. 8 shows the evaluated string-type cavitation thickness and occurrence of the cavitation in the nozzle sac. The string-type cavitation thickness was a normalized number that was calculated as a rate of thickness to the nozzle hole diameter *d* at the hole outlet. Fig. 9 shows the string-type cavitation thickness, occurrence of the cavitation in the sac and needle-lift during the

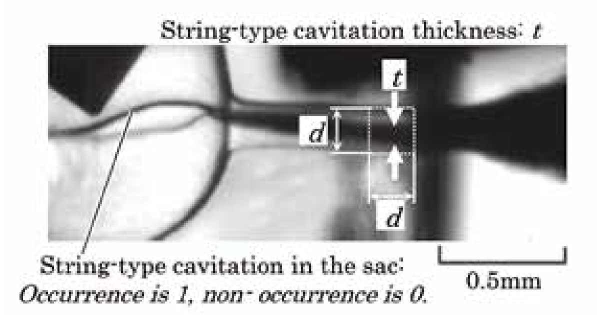

Fig. 8 Definition of cavitation profile

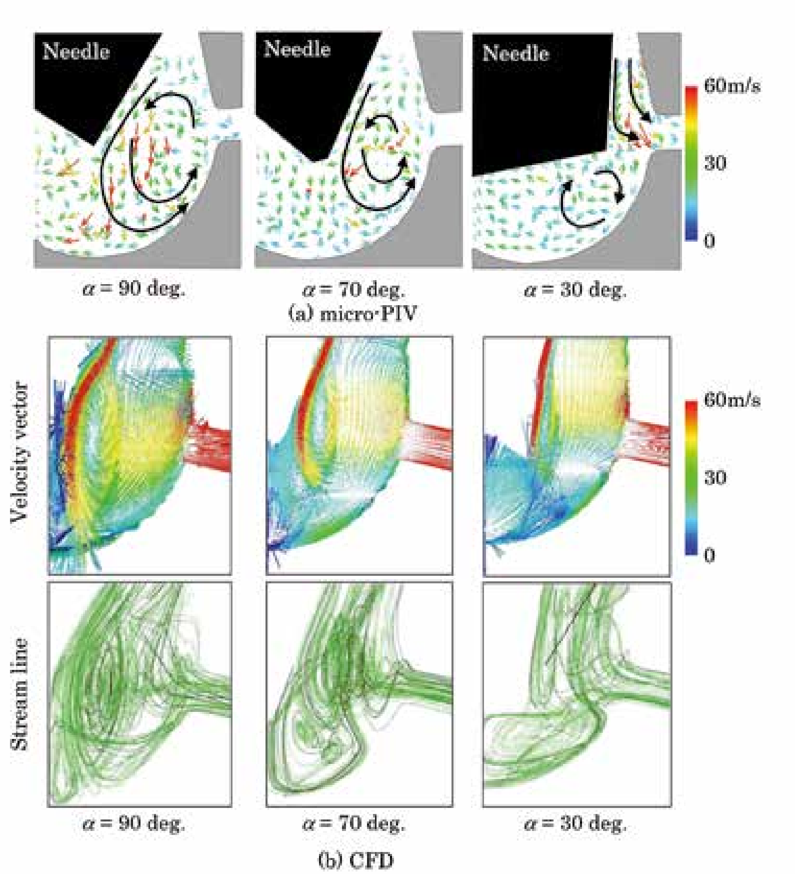

Fig. 7 Internal Flow by micro PIV and CFD at 0.2ms after start of injection (ASOI)

injection.

When the cavitation was connected in the sac, the string-type cavitation thickness t/d was large. There was a good correlation between the connection of the cavitation in the nozzle sac and the string-type cavitation behavior. In α=90 degree, the connection of the cavitation in the nozzle sac was frequently and the string-type cavitation thickness was large during the rise of the needle. In α=70 degree, the cavitation was observed in nozzle sac. However, the occurrence frequency of the cavitation in the nozzle sac was less than α=90 degree. Moreover, the string-type cavitation thickness was smaller as well. Finally, the string-type cavitation thickness of α=30 degree needle without the occurrence of the cavitation in the nozzle sac was small during the fuel injection.

The weak vortex flow with the small angle of needle tip decreased the occurrence frequency of the cavitation in nozzle sac and the string-type cavitation thickness in nozzle hole. These results are suggested that the weak vortex flow unable to connect the string-type cavitation in the nozzle hole and another hole is not able to develop the string-type cavitation originating from swirling flow of the nozzle hole which has been mentioned the past study [5, 6]. Thus, the vortex affected the string-type cavitation through the strength of the swirling flow in nozzle sac.

3.3 Effect of vortex flow on spray formation

Finally, the effect of the vortex flow in nozzle sac on the spray formation was confirmed. Fig. 10 shows the visualization images of the internal nozzle and the spray. In nozzle with α=90 degree needle, when the string-type cavitation formed clearly, a large spray cone angle was observed at 0.3ms ASOI. Then, in the nozzle with α=70 degree needle which the string-type

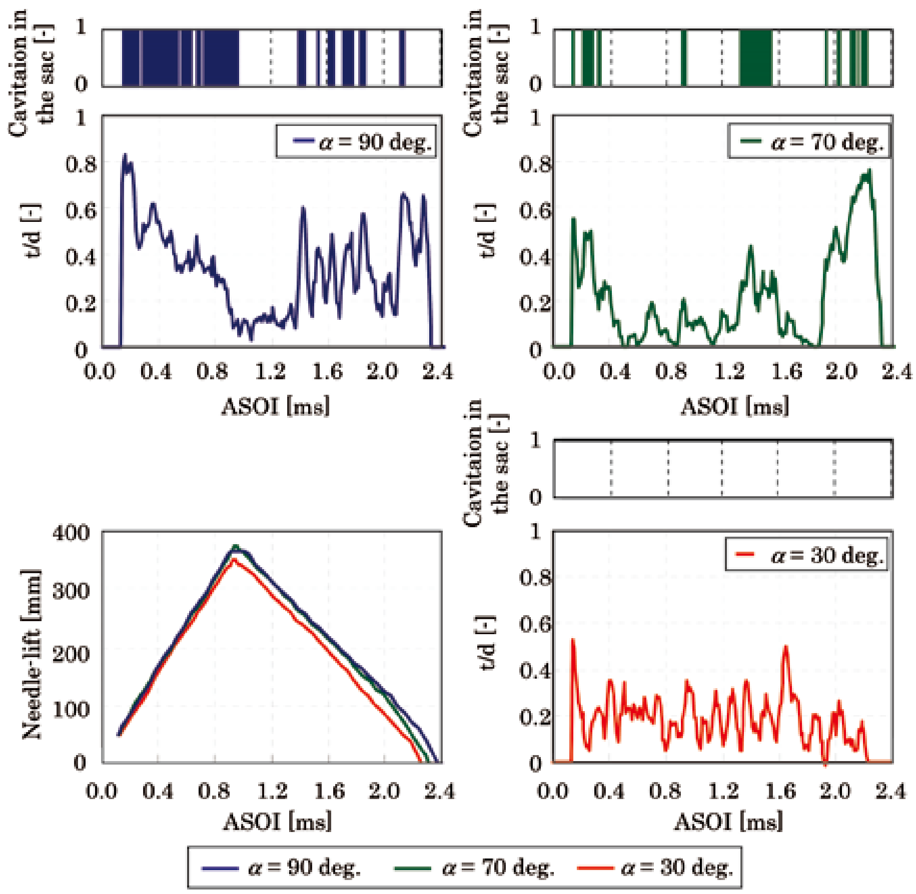

Fig. 9 Cavitaion characteristics

cavitation was weak, the spray cone angle was smaller than α=90 degree at 0.3ms ASOI. In contrast, the spray cone angle of nozzle with α=30 degree needle was small during the injection. These three types nozzle had a variation of the spray cone angle during 0.3ms ASOI to 0.8ms ASOI.

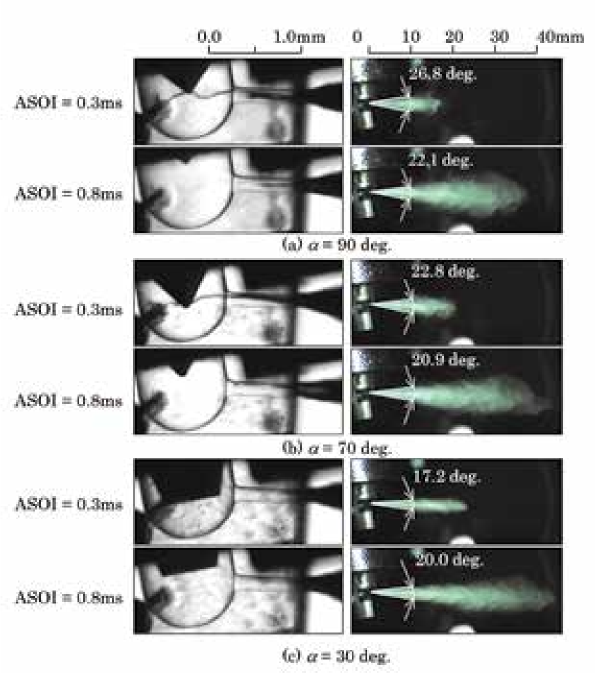

Fig. 10 Cavitaion and spray for a variation of the needle shape

Fig. 11 shows the rate of injection, string-type cavitation thickness, spray cone angle, and spray tip penetration from the start injection to 1.0ms ASOI. The rate of injection was calculated as equation (1), where q is a rate of injection with a single hole, F is a colliding force on a force sensor of the spray with the single hole, C is flow coefficient, A is cross-section area of the nozzle hole outlet, and ρf is density of the fuel[12]. When the string-type cavitation formed with high probability during 0.15ms to 0.30ms ASOI, the rate of injection of α=90 degree needle decrease. The rate of injection was influenced by the string-type cavitation. Next, the spray cone angle in proportion as the string-type cavitation thickness was changed during the fuel injection. Moreover, the maximum of the spray cone

$$q = \sqrt{\frac{F \cdot C \cdot A}{\rho_f}} \tag{1}$$

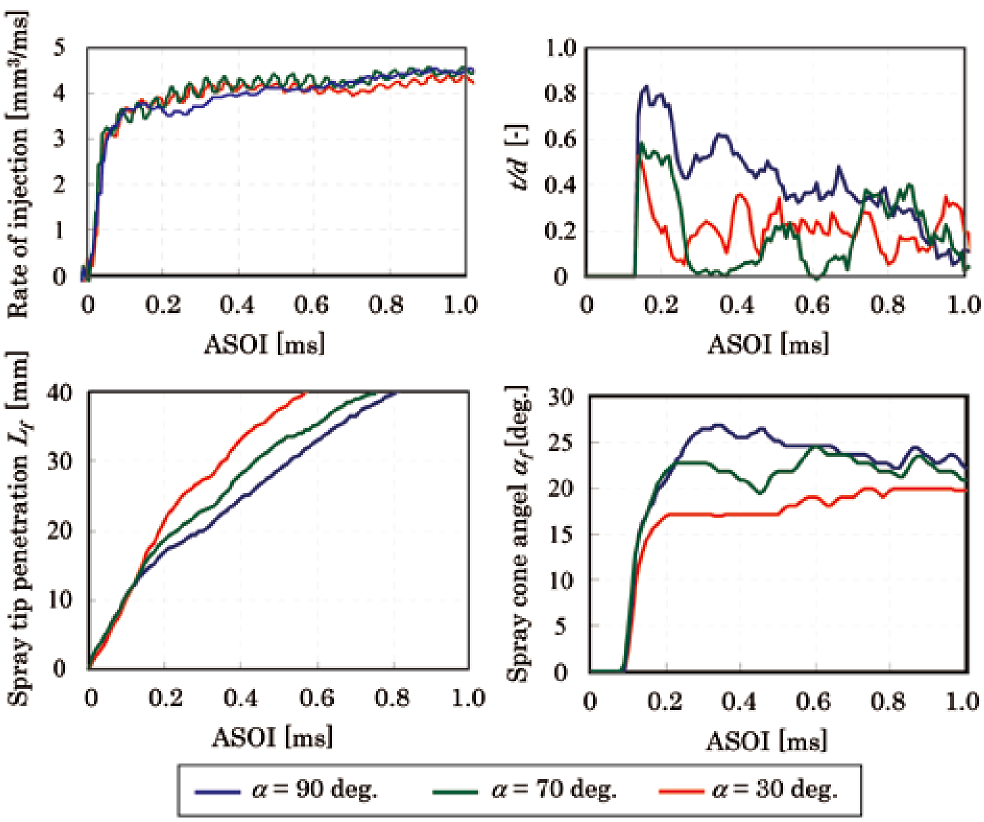

Fig. 11 Relation of string-type cavitation and spray characteristics

angle with each needle shape was decreased as well. Then, the spray tip penetration was strong in inverse proportion to the string-type cavitation. These results suggest that the string-type cavitation thickness shows the strength of radial direction velocity in nozzle hole. Because the strong radial direction velocity is able to raise the spray tip penetration and decrease the spray cone angle.

The small angle of the needle tip caused small spray cone angle, large spray tip penetration and stable rate of injection due to small string-type cavitation thickness. These results show that the spray characteristics are affected by the string-type cavitation: therefore, the vortex flow in nozzle sac affected the spray characteristics through the string-type cavitation behavior.

CONCLUSION

The relationship between the vortex flow, cavitation, and spray behavior of real-size diesel nozzle was analyzed by both experimental measurement and numerical simulation. In order to investigate the effect of the vortex flow by the shape of the needle tip, a flow was visualized by employing a transparent nozzle. The following conclusions were drawn:

1. The shape of the needle tip, which can control the vortex flow in the nozzle sac, was confirmed by the micro-PIV and CFD analysis of internal flow in the nozzle sac. In the nozzle with needle of small tip angle, the vortex flow was inhibited near the nozzle hole in the sac so that, the fuel near the sac inlet more smoothly flowed into the nozzle hole during the fuel injection. On the other hand, the large vortex flow in the nozzle sac was formed near the nozzle hole by the nozzle with the needle of large tip angle.

2. The weak vortex flow with the small angle of needle tip decreased the occurrence frequency of the cavitation in nozzle sac and the string-type cavitation thickness in nozzle hole. These results are suggested that the weak vortex flow unable to connect the string-type cavitation in the nozzle hole and another hole is not able to develop the string-type cavitation originating from swirling flow in the nozzle hole. Thus, the vortex in nozzle sac affects the string-type cavitation through the strength of the swirling flow in nozzle sac.

3. The small angle of the needle tip is caused for small spray cone angle, large spray tip penetration and stable rate of injection due to stable small string-type cavitation thickness. These results show that the spray characteristics are affected by the string-type cavitation: therefore, the vortex flow in nozzle sac affect the spray characteristics through the string-type cavitation behavior.

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APPENDIX

Notation

n	Number of holes
d	Nozzle hole diameter (mm)
L	Nozzle hole length (mm)
α	Angle of the needle tip (degree)
R	Inlet radius of the hole (mm)
T_a	Ambient temperature (K)
P_a	Ambient pressure (MPa)
P_v	Vapor pressure of the fuel (MPa)
P_{inj}	Injection pressure (MPa)
u	Flow velocity inside the nozzle hole (m/s)
ν	Dynamic viscosity (m^2/s)
Re	Reynolds number
CN	Cavitation Number
t_{inj}	Injection duration (ms)
t	String cavitation thickness (mm)
L_f	Spray tip penetration (mm).
α_f	Spray cone angle (degree)

Abbreviations

MS	Mini-Sac
PIV	Particle Image Velocimetry
CFD	Computational Fluid Dynamics
RANS	Reynolds Averaged Navier-Stokes Simulation
ASOI	After Start of Injection [ms]

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