Effect of Internal Flow in a Simulated Diesel Nozzle on Spray Characteristics

H. Gen Fujimoto[1], K. Tanaka[2], H. Kuzuwata[1] and J. Senda[1]

1. Department of Mechanical Engineering, Doshisha University
Miyakodani 1-3, Tatara, Kyotanabe, 610-0321 JAPAN
2. Matsushita Electric Industrial Co., Ltd., Kadoma 1006, Kadoma, 571-8501 JAPAN

The internal flow in a sack and a nozzle hole of a diesel nozzle has the great influence on the spray characteristics. The authors paid notice to this effect and reported the case of a simulated 2-D model nozzle. This report describes firstly the result of flow in the sac and a nozzle hole obtained by the numerical calculation. The others are the experimental results carried out in a 3-D simulated model nozzle under the condition of the steady state.

1. Introduction

The atomization of fuel is the key factor of good combustion and exhaust emission through a CI engine as well as an SI engine. The cavitation phenomenon in side an injection nozzle affects the atomization characteristics as pointed out by Bergwerk [1] using a transparent nozzle for the first time. Eifler [2] took the photograph of the phenomenon by high-speed photography with speed of 100,000 [fps]. Many researchers have taken an interest in the cavitation phenomenon since he presented it in his work, and they published their works [3]-[12]. They carried out their experiments in the transparent model nozzle whose size much larger than that of an actual nozzle. The reason why was that the actual nozzle is too much small to visualize inside the nozzle.
The authors reported the discharge coefficient and the spray cone angle related to the cavitation phenomena also by use of the simulated 2-D model nozzle with two times magnification [13]. This report describes the comparison of the internal flow inside this nozzle shown in the reference [13] with that obtained by the numerical calculation and the experimental results obtained through the simulated 3-D model nozzle.

2. Calculation of internal flow in simulated 2-D model nozzle

The internal flow in the simulated 2-D model nozzle with two times magnification was simulated by the hydraulic analysis code (Adaptive Research: CFD2000) and compared with that obtained in the experiments. The assumptions were 2-D, the incompressible fluid and the turbulent viscous flow. The dominants were the equation of continuity, that of Navier-Stokes and that of turbulent kinetic energy. And the turbulence was dominated by k-ε model. Table 1 summarizes the condition of calculation.
Figure 1 is one of examples of the comparison of internal flow in the case of experiments with that of calculation. The diameter of tracer was ranged from 48 [μm] to 52 [μm] and its specific weight was 1.03. The internal flow was taken by photography through the transmitted light of a halogen lamp. The vortex appears at the left hand side of the sac in both results. The other vortex that is smaller than the former breaks out at the right hand side in the calculation, however, it does not recognize in the experiments. The reason why is that the tracer does not follow the slower velocity at this area. Nevertheless, the calculation expresses well the internal flow obtained in the experiments. However, the code is not built in the cavitation mechanism. When the method of the volume of flow is applied to this code putting in the pressure equation related to the nuclei, it is able to calculate the internal flow with the cavitation phenomena.

Table 1 Condition of calculation in case of simulated 2-D model nozzle

Fluid	n-tridecane	
	Kinematic viscosity ν [m^2/s]	2.33×10^{-6}
	Density ρ [kg/m^3]	765.6
Differencing schemes	Finite volume method	
Turbulent model	Standard k - ε model	
Initial condition	Flow velocity [m/s]	0
	Temperature [K]	293
	Pressure [MPa]	0.1
Boundary condition	Inlet Pressure [MPa]	2.0, 5.0
	Outlet Pressure [MPa]	0.1
	Wall Condition	Non-Slip
Calculating condition	Time Step [s]	2.87×10^{-7}
	Calculation Time [s]	1.00×10^{-2}
	Number of Grid	5440

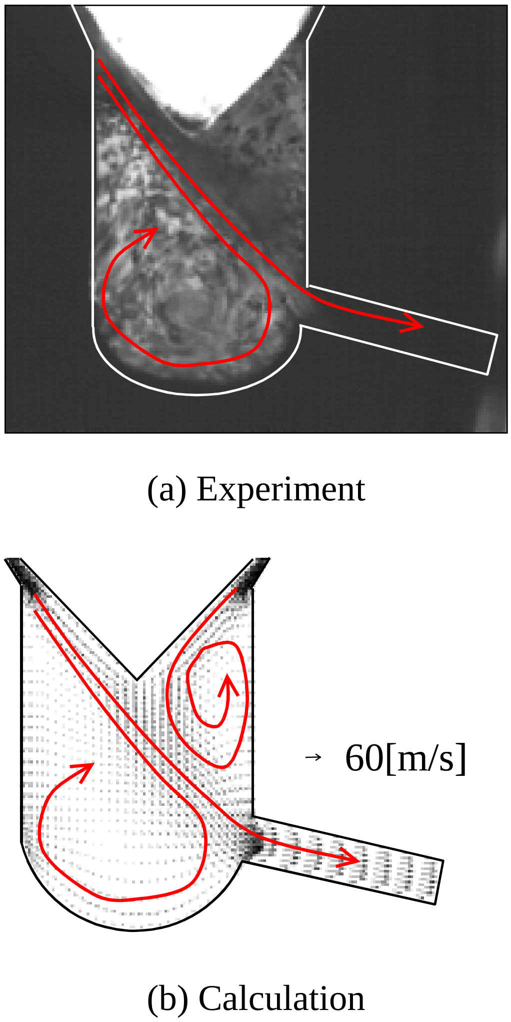


Fig. 1 Internal flow in sack part and nozzle part of 2-D simulated model nozzle (fuel: n-tridecane, hole angle = 78 [deg.], needle lift = 0.2 [mm], p_{inj} = 2.0 [MPa], cavitation number = 0.053)

3. Experiments in case of simulated 3-D model nozzle

3.1 Cavitation number

The cavitation number, *K*, used is as follows [14]:

$$K = \frac{(p_a - p_v)}{(p_{inj} - p_a)} \quad (1)$$

where p_a is the ambient pressure, p_v is the saturated vapor pressure and p_{inj} is the injection pressure.

3.2 Experimental setup, procedure and conditions

3-D model expresses the phenomenon in an actual nozzle more than 2-D model. Figure 2 is the section of simulated 3-D model nozzle. It is made of acrylic resin and two nozzle holes are arranged symmetrically. The enlargement of dimension of this nozzle is twice as much as that of the objective nozzle. Ii is not always corresponds the relation between the needle lift and the minimum sectional area of the seat of the model nozzle to that of the objective one as shown Figure 3. The relation of the former expresses well that of the latter compared with the case of 2-D model nozzle [13]. The contraction of the hole is larger than that of the seat when the needle lift is under 0.0683 [mm]. Then, the needle lifts of the model nozzle of 0.2 [mm] and 0.4 [mm] were selected in the experiments. The hole angle was 30 [deg.], 60 [deg.] and 78 [deg.], respectively. The fuel used was n-tridecane as the reference of gas oil supplied to a high-speed diesel engine. The other was the mixed fuel composed of n-pentane and n-tridecane and the molar fraction of each component was equal.
The experimental procedure was just same as that of the former report [13]. Namely, the fuel injected into the atmosphere under the steady state. The flow inside the model nozzle and the spray were taken simultaneously by a high-speed video camera (KODAK, EKTAPRO HS Motion analyzer, Model 4540) with speed of 4500 and 9000 [fps] through the transmitted light whose source was a halogen lamp. The enlarged photograph was taken to capture the cavitation

phenomena in detail in a part of experiments. Table 2 summarizes the experimental conditions. The variables are the injection pressure, in other words, the cavitation number.

The cavitation phenomenon fluctuates although the injection is steady. Then, the ratio of the area of cavitation region to that of nozzle hole (hereinafter called the area ratio of cavitation) is defined to express the fluctuation. The average boundary of the luminosity between the area of the cavitation and that of the non-cavitation was measured on the image by using threshold. The discharge coefficient at the nozzle outlet is one of the key factors considering the cavitation phenomena. The coefficient was calculated by use of the theoretical flow rate and the mass of the flow received at the nozzle outlet.

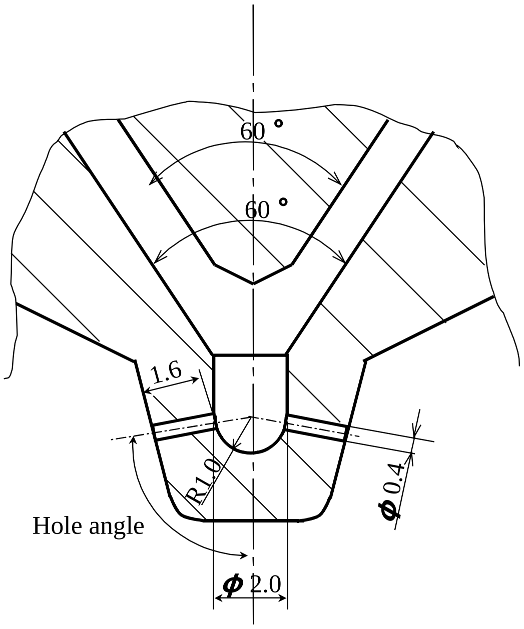
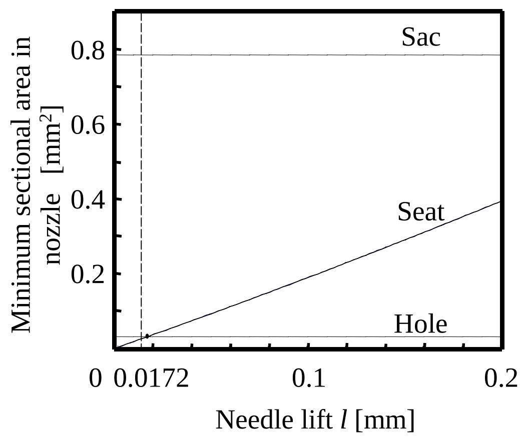


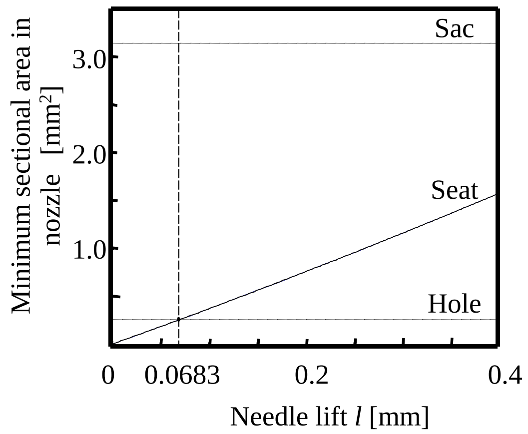
Fig. 2 Section of simulated 3-D model nozzle

Table 2 Experimental conditions

Hole angle θ [deg.]	30		60		78
Needle lift $\boldsymbol{L}$ [mm]	0.2		0.4		
Cavitation number K	0.053 or 0.039	0.034 or 0.024	0.026 or 0.019	0.020 or 0.015	
Injection pressure p_{inj} [MPa]	2.0	3.0	4.0	5.0	
Ambient pressure p_a[MPa]	0.1				
Fuel temperature T_f[K]	293				



(a) Objective nozzle



(b) 3-D,two magnified model nozzle

Fig. 3 Minimum sectional area of seat as a function of needle lift

4. Experimental results

4.1 Internal flow in sack

Figure 4 displays one of examples of the internal flow against the hole angle. The black zone corresponds cavitation babbles. The time difference, Δt, of each image is 0.1 [ms]. In the case of the hole angle of 78 [deg.], the string cavitation [6] appears and disappears frequently. However, this kind of phenomenon does not break out in the other hole angle. It seems that the cause of this trend is the flow in the sack. Namely, the fluid in the sack is smoother, consequently, flows more easily to the nozzle hole, and the area of the contraction is smaller in the case of the small hole angle than those in that of the large hole angle.

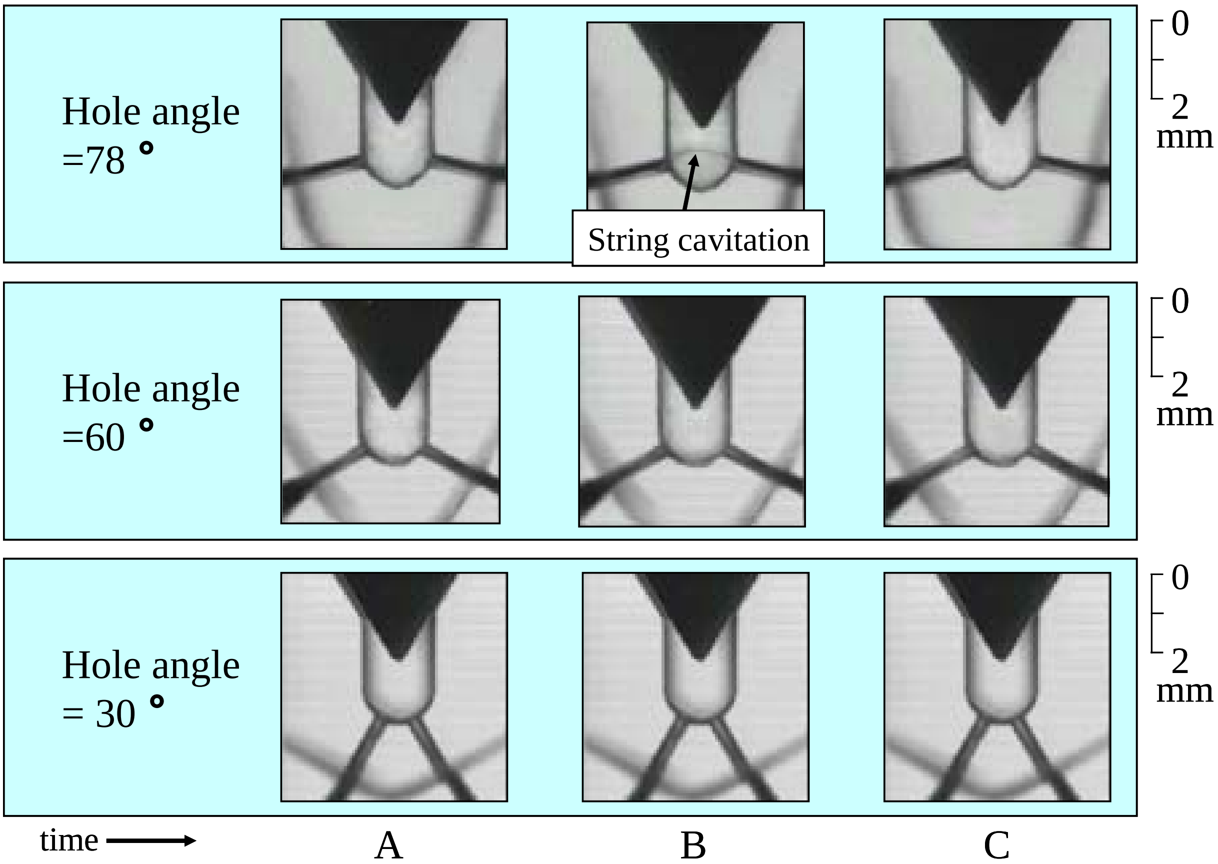


Fig. 4 Internal flow against hole angle
(needle lift = 0.2 [mm], p_{inj} = 2.0 [MPa], K = 0.053, Δt = 0.1 [ms])

4.2Relation between internal flow in sack and spray

Figure 5 is one of examples of the sequential photographs of internal flow. The time difference, Δt is 0.1 [ms]. The string cavitation breaks out near outlet of both nozzle holes and they grow in the direction of the inlet of nozzle hole (A). Then, they connect each other in the sac (B). At the photograph (C), the string cavitation disappears, simultaneously, the spray spreads in the radial direction, because the cavitation babbles discharge from the nozzle outlet and they break. After the break out of cavitation bubbles (D) the spray cone angle becomes nearly equal to that in the case (A). The frequency of break out of the string cavitation becomes larger and the period of its existence does longer as the increase in the injection pressure. The string cavitation generates easily when the hole angle increases and the fuel used is mixed fuel.

4.3 Relation between cavitation area and spray cone angle

Figure 6 shows one of examples of sequential images (a) and their schematic (b) in the case of no string cavitation in the sac, however, the cavitation appears in the nozzle. It fluctuates and there is the irregularity at the boundary between the cavitation area and the flow area as shown by a red arrow although the needle lift is fixed. Accompanying the change in the cavitation area, the spray cone angle also varies. When the cavitation area separates from the upper side as shown in D, the spray cone angle increases. The injection duration of an actual high-speed diesel engine is ranged from about 1 [ms] to 5 [ms]. The duration corresponds from 4 [ms] to 20 [ms] in the simulated model nozzle presented here. The time difference, Δt, of each image in Figure 4, 5 and 6 is only 0.1 [ms]. Namely, the fluctuation of spray cone angle surely occurs in the actual engine and affects the engine performance.

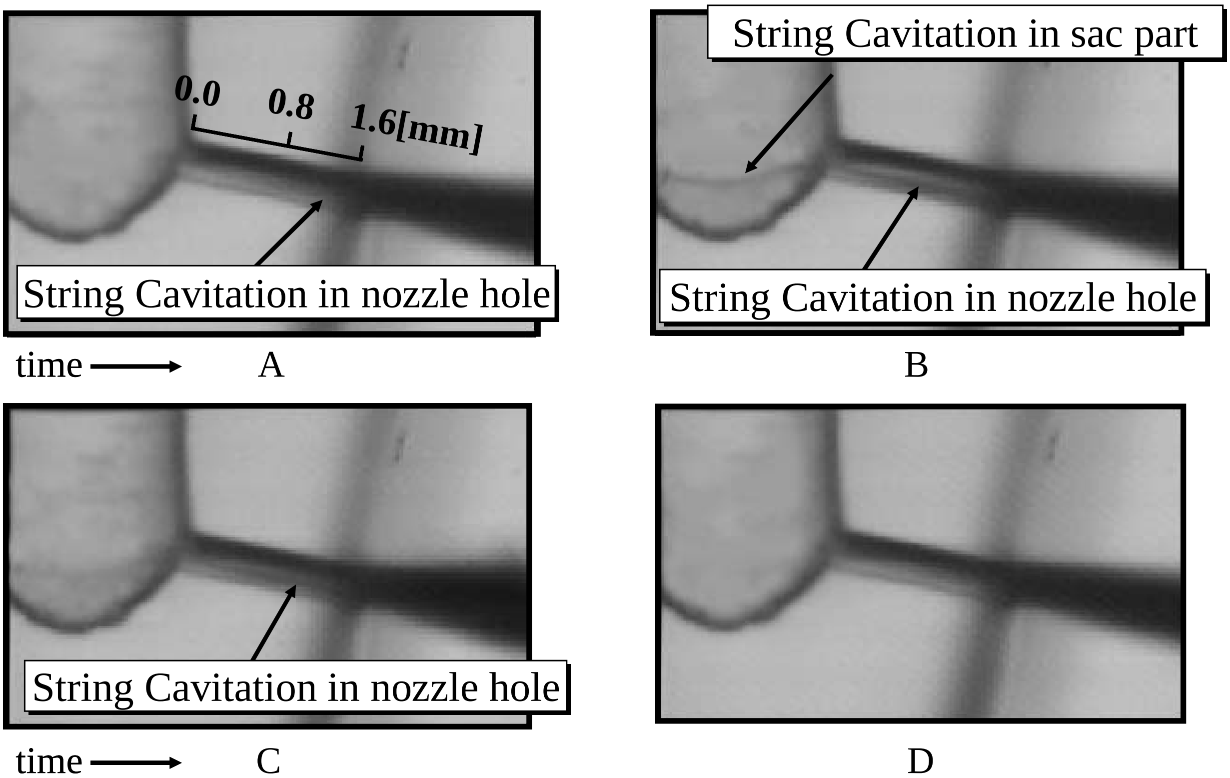


Fig. 5 Generation process of string cavitation
(hole angle = 78 [deg.], needle lift = 0.4 [mm], p_{inj} = 4.0 [MPa], K = 0.026, Δt = 0.1 [ms])

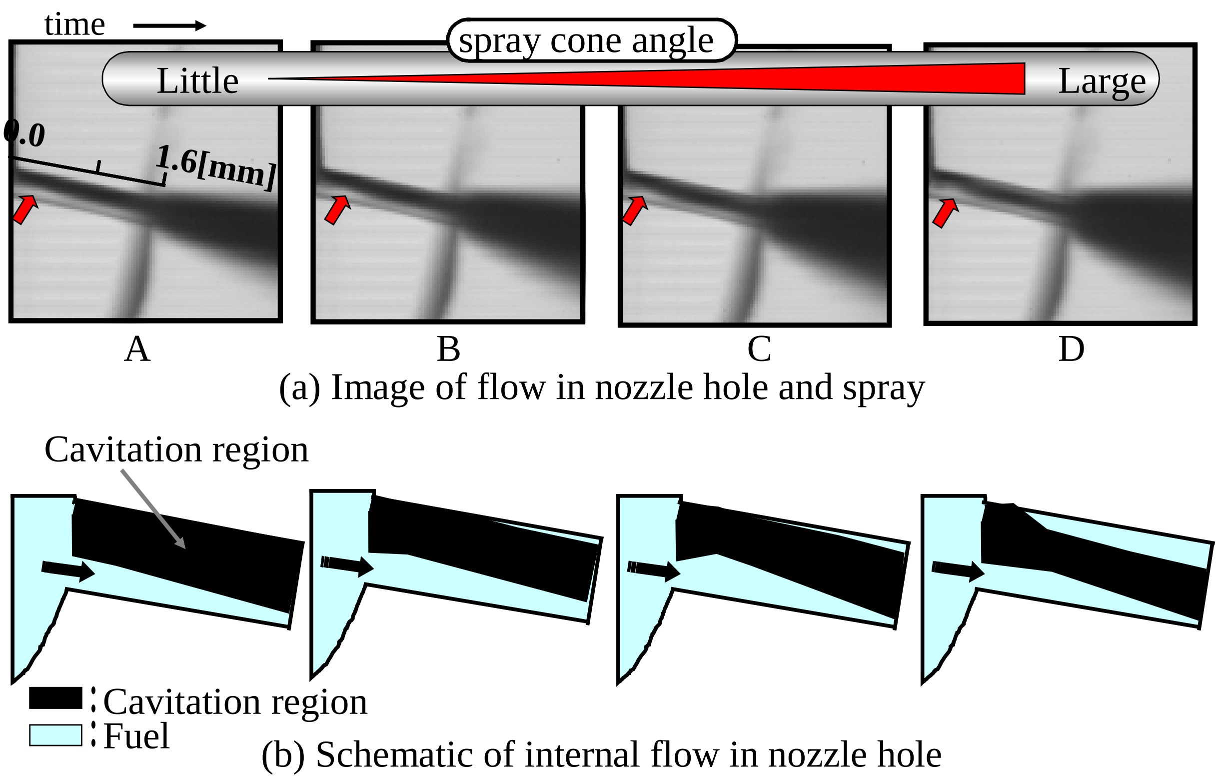


Fig.6 Images of flow in nozzle hole and spray and schematic of flow in nozzle hole
(hole angle = 78 [deg.], needle lift = 0.2 [mm], K = 0.053, p_{inj} = 2.0 [MPa], Δt = 0.1 [ms])

Figure 7 shows one of examples of the temporal fluctuation of the area ratio of cavitation and Figure 8 does that of the spray cone angle. Figure 9 is also one of examples of the relation among the average area ratio of cavitation, the average spray cone angle and the cavitation number and Figure 10 is that among the average discharge coefficient, the cavitaion number and the hole angle.

Both the area ratio and the spray cone angle show much fluctuation as elapsing the time. The case of the mixed fuel shows just the same trend as that of the pure fuel. The area ratio, the spray cone angle and the discharge coefficient are larger as the cavitation number is smaller. The reasons of these trends are mentioned in the former section. In the case of the mixed fuel, the average spray cone angle is larger than that of n-tridecane, although the average area ratio of cavitation is nearly equal each other. The tendency is caused by the generation of the flash boiling phenomena in the mixed fuel. When the needle lift becomes small, the cavitation ratio and the spray cone angle become small as the fluid in the sack flows into the nozzle smoothly, its velocity increases and the area ratio increases. The smaller the hole angle is, the larger the discharge coefficient is. The reason for this tendency why is that the flow becomes smooth as shown in Figure 4. In the case of simulated 2-D nozzle, the average spray cone angle shows the reverse trend of the discharge coefficient against the cavitation number [13]. It seems that this trend of 2-D nozzle does not always correspond to that of the actual nozzle.

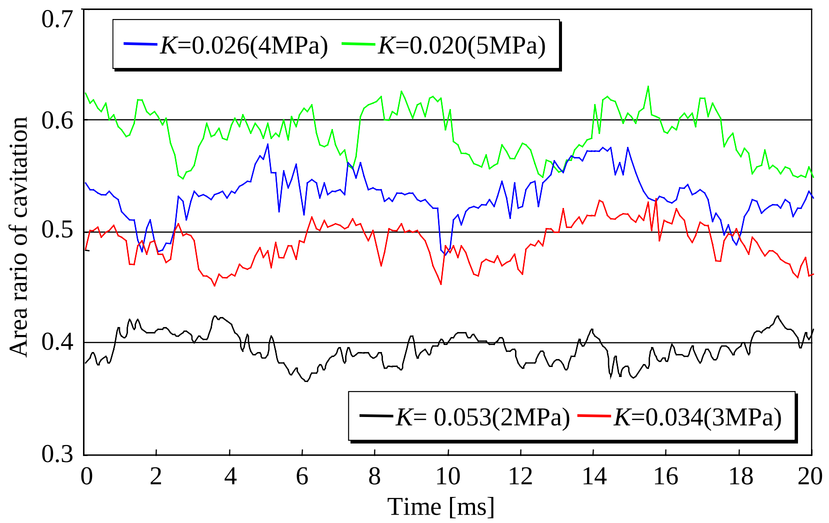


Fig. 7 Temporal fluctuation of area ratio of cavitation
(hole angle = 78 [deg.], needle lift = 0.2 [mm])

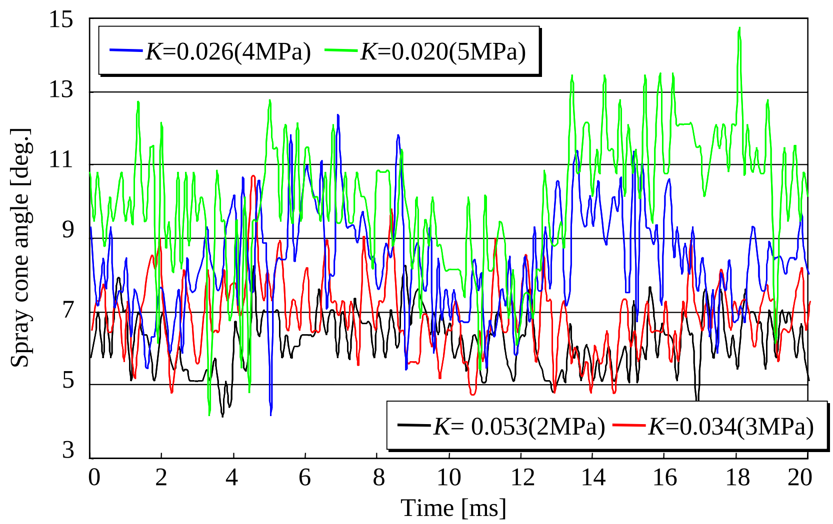


Fig. 8 Temporal fluctuation of spray cone angle
(hole angle = 78 [deg.], needle lift = 0.2 [mm])

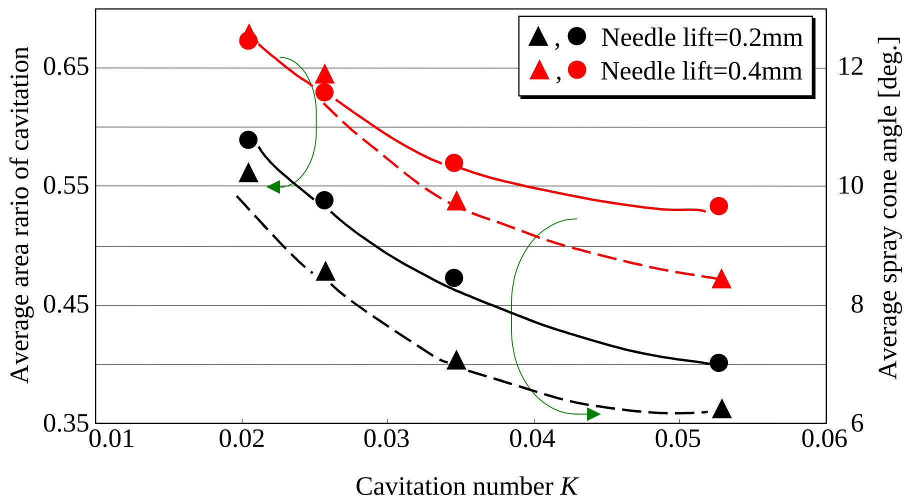


Fig. 9 Relation among averaged area ratio of cavitation, average spray cone angle and cavitation number (hole angle = 78 [deg.])

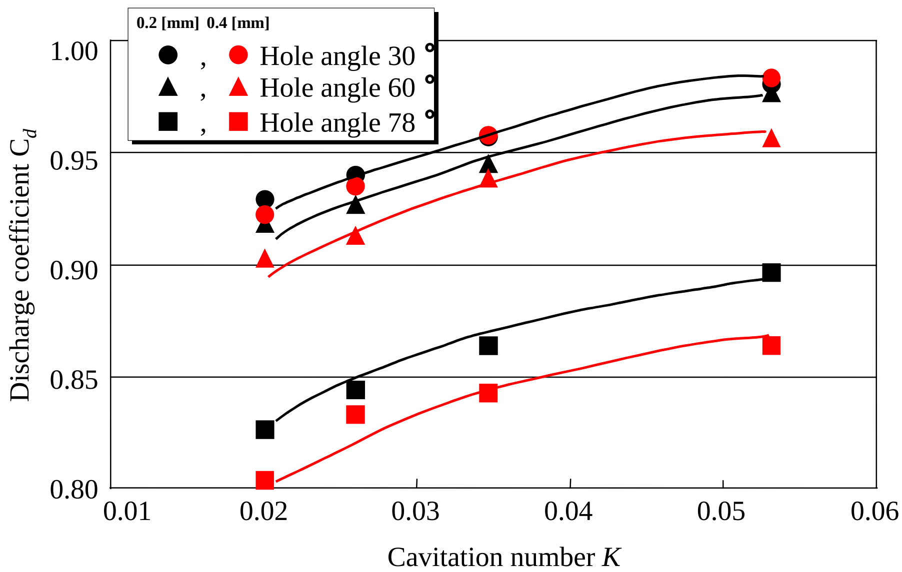


Fig. 10 Relation among discharge coefficient, cavitation number and hole angle (hole angle = 78 [deg.])

4.4 Relation between temporal fluctuation of area ratio of cavitation and that of spray cone angle

It is estimated through the experimental results mentioned above that there is the close relation between the temporal fluctuation of the area ratio of cavitation and that of the spray cone angle. The frequency analysis by FFT method as for the temporal fluctuation of the area ratio of cavitation and that of the spray cone angle was performed to confirm this estimation. Figure 11 is one of the results. The frequency at the peak of power that is indicated by an arrow almost corresponds in both cases of the area ratio and the spray cone angle each other. Namely, it is the evidence that the former fluctuation causes the latter one.

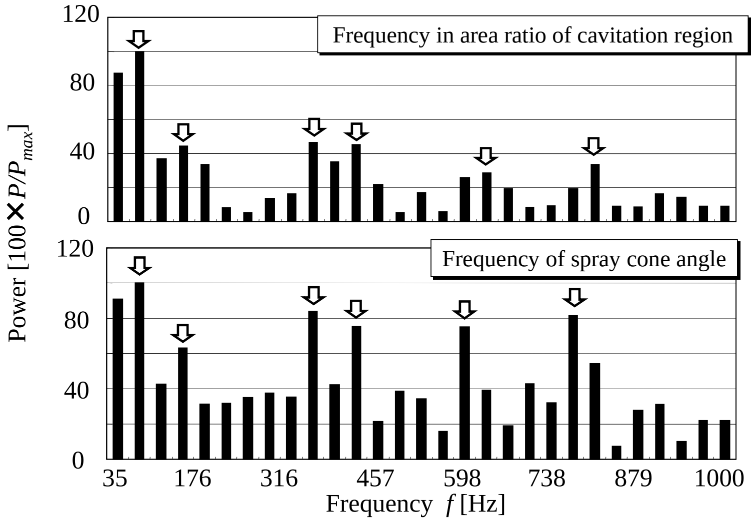


Fig. 11 Frequency analysis of area ratio of cavitation and spray cone angle
(hole angle = 78 [deg.], needle lift = 0.2 [mm], K = 0.026, p_{inj} = 4.0 [MPa])

5. Conclusion

The following conclusions are drawn from the results:

1. The internal flow in sac part and nozzle part of the simulated 2-D model nozzle obtained by numerical calculation expresses well that shown in the experiments.
2. The string cavitation occurs not only in the sack but also in the nozzle. The larger the hole angle and the cavitation number are, the more the string cavitation breaks out. This kind of cavittion occurs easily in the case of mixed fuel.
3. The area ratio of cavitation and the spray cone angle fluctuate as the time elapsing although the injection is steady. The both peak of the fluctuation almost correspond each other. Namely, the fluctuation of the former causes that of the latter. The phenomenon occurs in n-tridecane as well as the mixed fuel.
4. As the needle lift increases and the cavitation number decreases, the area ratio of cavitation and the spray cone angle increases.
5. When the hole angle becomes smaller, the discharge coefficient becomes larger.
6. In the case of mixed fuel, the area ratio of cavitation is almost the same as that of the pure fuel, however, the spray cone angle of the former is larger than that of mixed fuel.

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