# Experimental Study on Unsteady Fuel Spray Impinging onto a Projection on a Wall

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## ABSTRACT

As a fundamental work on a Direct Injection Impinging Diffusion Combustion Engine, a fuel spray was injected instantaneously into a pressured $CO_2$ gas and impinged onto a projection on a wall. Instantaneous photographs were taken and analyzed to clarify the spray characteristics. Nozzle opening pressure was varied to clarify its effects on spray characteristics. A nozzle needle was cut to form two pairs of flats on its needle surface instead of its cylindrical one. The effect of this needle shape was also studied. Opening pressure of the injection nozzle has produced very little effect on the spray tip penetration. Spray thickness is larger when the needle opening pressure of injection nozzle is high. Spray tip penetration and spray thickness have become large when widths across flats is narrow.

## INTRODUCTION

New mixture formation and combustion processes named OSKA have been developed by Kato and Onishi (1–6)[1]. In OSKA, the fuel is injected against the impinging surface and spreads radially after the impingement.

The spray characteristics plays a very important role on emission and performance characteristics in the OSKA system. For instance, Kato has reported that relatively low injection pressure obtains better emission performance (4). Kato has recently applied a nozzle whose needle has two pairs of flat surfaces cut on its cylindrical surface to the OSKA engine and obtained further good emission and performance characteristics (6).

The mixture formation process, however, has not been satisfactorily clarified so far as concerning this type of spray.

Naber, et. al. have reported the KIVA simulation of the OSKA type spray and compared with a bomb experiment (7). They reported that the simulation indicated fairy good agreement with experimental one and the further modification of model was required. Nishida and Hiroyasu injected the spray against the pin in a pressure vessel (8). In their experiment, projection pin is high compared with that of an actual OSKA condition. Watanabe has reported the characteristics of the OSKA type spray using the liquid-liquid injection technique (9).

Authors have reported the entrainment characteristics of the OSKA type spray using unsteady gas jet simulation, where the time and space resolved distribution of concentration and of pressure were obtained (10). The air is entrained both upper and lower surfaces of OSKA type spray as shown in Fig. 1, on the other hand, in the ordinary wall impinging spray the air is entrained only one surface because another surface contacts with the wall.

The OSKA type spray grows both upward, that is, a nozzle direction, and downward while it spreads radially. The OSKA type spray consequently entrains more air. The spray is then attracted against the wall because the pressure between the spray and the wall is lower than surrounding one due to the air entrainment from the lower surface. Smaller distance between the impinging surface and the piston cavity bottom results in quicker pressure decrement and faster spray attraction. After the spray reaches the wall the spray becomes an ordinary wall spray. This means that the distance between the impinging surface and the cavity bottom is one of the most dominant parameters of the OSKA system.

In this paper the authors have studied the characteristics

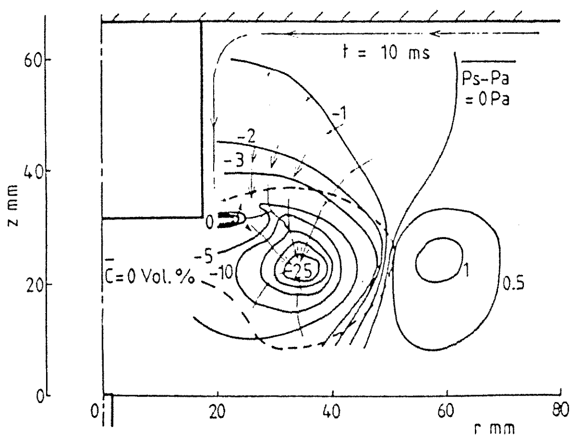


Fig. 1. Static Pressure Distribution in Unsteady Gas Jet Impinging onto a Projection on a Wall (10)
A dashed line indicates the jet boundary obtained from instantaneous concentration. Arrows indicate flow motion.

[1] Numbers in parentheses designate the reference listed at the end of paper.

of the OSKA type spray injected into a quiescent high pressure gas at various injection pressures and with various injection needles. The spray photograph was taken and analyzed to get spray characteristics.

## EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment was carried out by injecting gas oil from a pintle nozzle against the impinging part on a wall settled in a vessel filled with a $CO_2$ gas of corresponding density of that at the injection start of an actual OSKA engine, and by taking instantaneous photographs of the spray.

Figure 2 shows a schematic illustration of experimental apparatuses. A vessel **5** has a large enough inner volume compared with that of the spray, and has optical windows.

Impinging part **2**, whose diameter is 10 mm, was screw-fitted on a transparent wall **3**, which corresponds to the bottom of the piston cavity. Distance between the impinging surface of the impinging part and the wall was changed by using various lengths of the impinging part. The wall was settled in a vessel using a precision positioning device **4** to adjust the distance between the injection nozzle **1** and impinging surface.

Fuel injection was made using a by-pass type single shot system composed of a Bosch inline injection pump **9**, a by-pass nozzle **6** and a main nozzle **1** in order for fuel to be injected similar injection pressure history to the actual engine. The main nozzle used was identical to that used in the actual OSKA engine.

Instantaneous photographs of the spray were taken using a micro flash **18** whose duration is 0.5 μs. The injection start was detected by a nozzle lift pick up **14** and it triggered the retarding circuit.**16**. After the preset time, which was determined based on a preferred number, a micro flash was excited to expose the spray. The scattering light was taken on a 35 mm still camera **20**.

The spray injected from a nozzle with the square needle was not an axially symmetric one, therefore both side view and bottom view observations of the spray are required. The scattering light goes via two different light paths simultaneously. One path is for the horizontal view of the spray and another is for the bottom view. To get bottom view path a reflecting mirror was placed beneath the wall. The length of two optical paths are identical with help of auxiliary mirrors.

Figure 3 shows the nozzle and the needle of the injector used in the experiment. A needle was squared, that is two pairs of opposite flat surfaces are planed on its cylindrical surface with various widths, *s*, across flats, to clarify the effect of the needle shape. An ordinary cylindrical needle was also employed in the experiment of opening pressure clarification. Injection conditions are listed in Table 1.

The photograph was analyzed using the filmotion analyzer measuring the coordinate of spray periphery. Coordinates of the spray periphery were sent to a micro computer via a serial interface and stored in a disk.

From the coordinates sent from the filmotion analyzer, it was recalculated so that the square top of bottom view spray has the identical angle by rotating the coordinate system. Then the representative values of spray characteristics schematical-

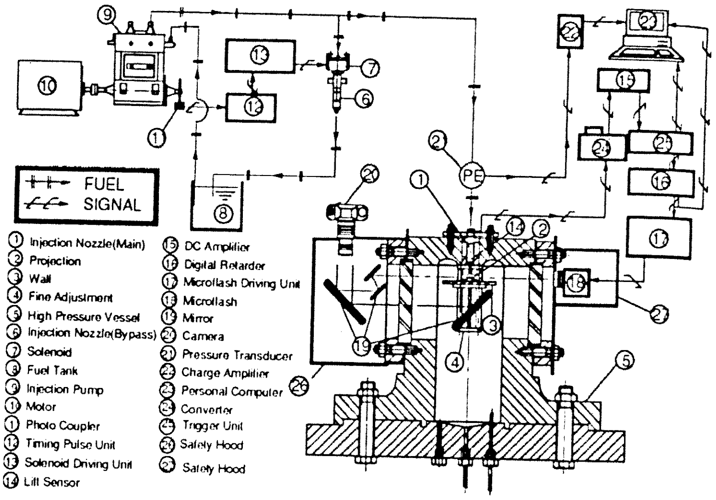


Fig. 2 Experimental Apparatus

Table 1 Injection Condition

| | |
|---|---|
| Injection Pump Speed | 1000 rpm |
| Injection Period | 0.68 ms |
| Opening Pressure of Injection Nozzle | 16.0 MPa |
| Nozzle Type | Pintle Nozzle |
| Widths Across Flats | 0.68, 0.79, 0.83 mm |

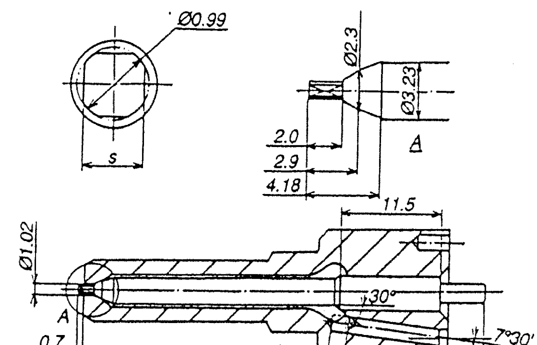


Fig. 3 Injection Nozzle Tip

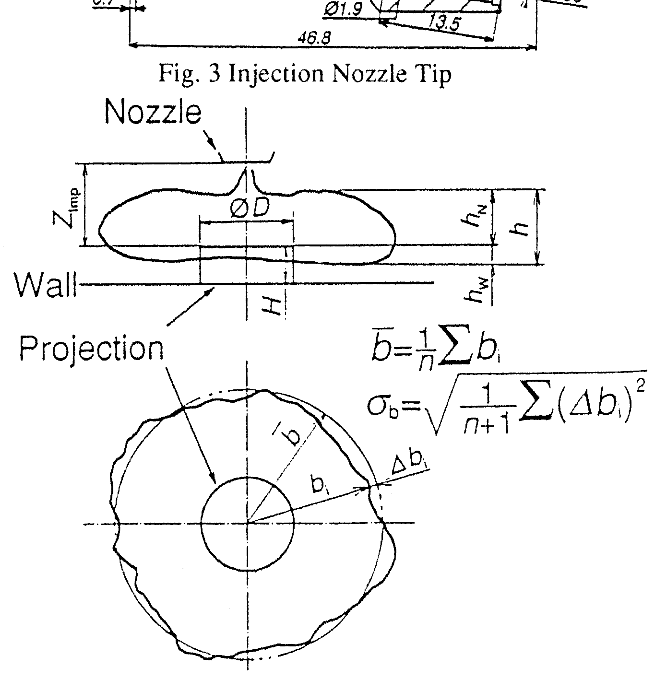


Fig.4 Spray Model

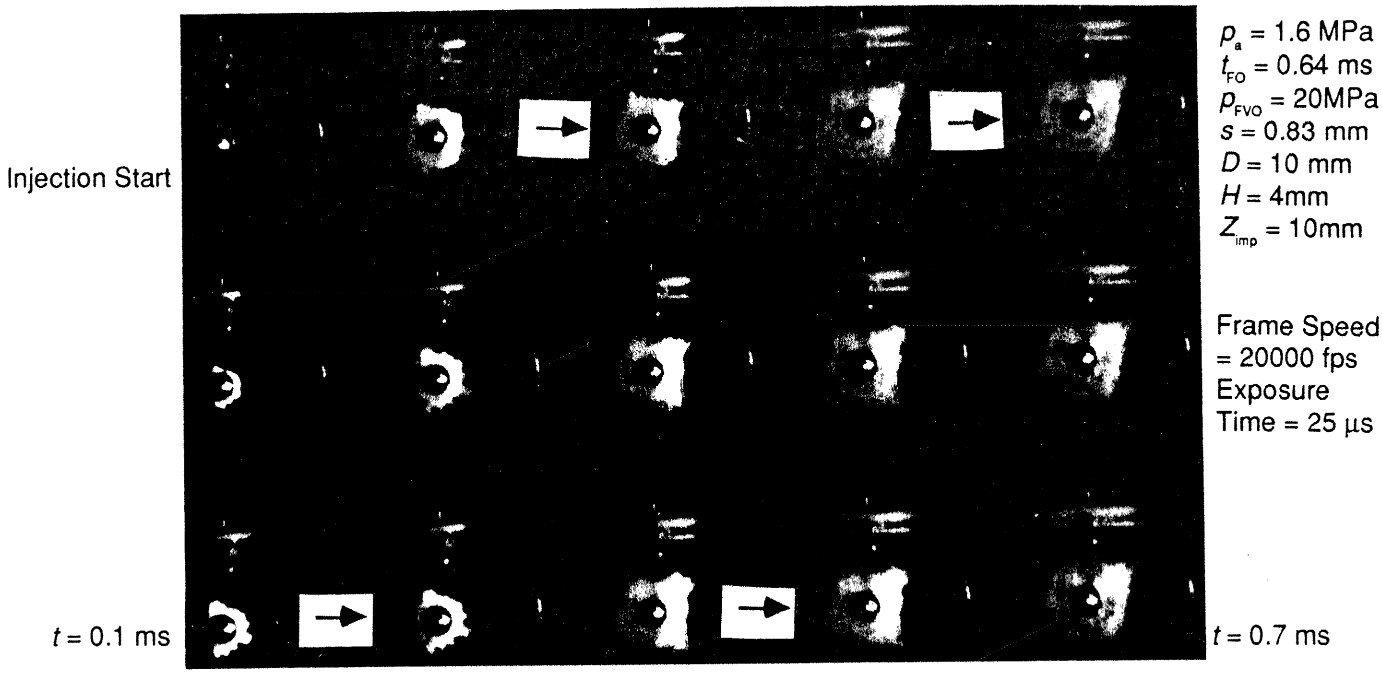


Fig. 5 High Speed Photograph of Spray

ly defined in Fig. 4 were calculated.

As turbulent mixture formation occurs in the spray, the position of the spray periphery scatters against the trial in microscopically even at the same time from after the injection start and even under the same injection condition. The coordinates of the spray periphery therefore were statistically computed, where the trial number of experiments at each time under each condition was determined as ten.

## PRELIMINARY EXPERIMENT

The nozzle needle might spin and might cause spray turn against its axis. High speed photographs were taken to confirm whether the spray turns within a single injection shot or not using an image converting type camera (Ultra Nac) and a metal halide lamp of 500 W instead of a still camera and a microflash respectively. Experimental setups, including the optical systems except the light source and the camera, were identical as indicated in Fig. 2

Figure 5 shows a typical example of a sequence of spray development taken with the image converting camera. From the figure, the spray turning motion is negligible within a single injection.

The still camera, on the other hand, takes different shots of the spray on each frame. The taken spray looks as if it turned, when the different shots of the spray photographs are simply joined with respect to the time after the injection starts, because the nozzle needle turns very slowly whose turning motion cannot be negligible in this case. The effect of this turning motion is compensated in the analysis process.

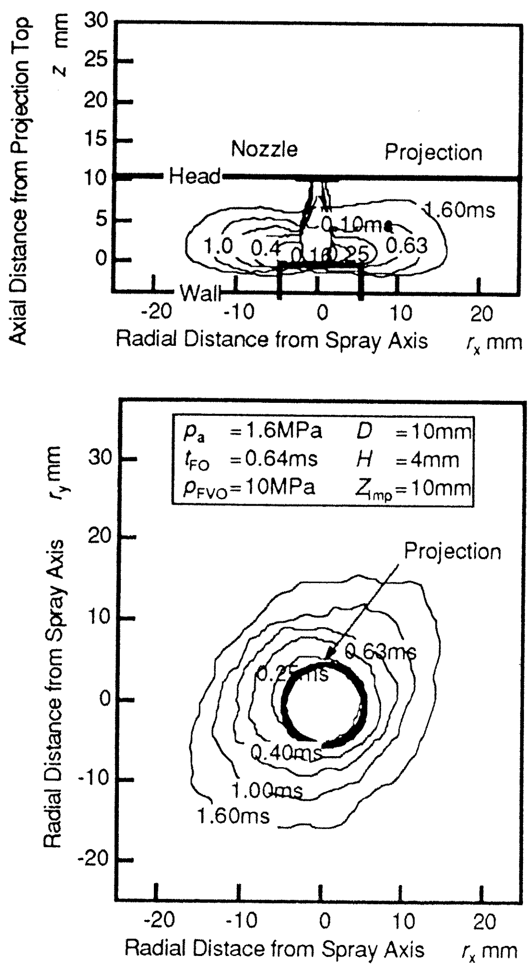


Fig. 6 History of Spray Trajectories Injected from a Nozzle with Cylindrical Needle

## EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 shows a typical example of a history of spray trajectories of the OSKA spray.

From the side view observation indicated in the upper part of each figure, a spray tip rolls up toward the injection nozzle as well as the spray grows in a radial direction like an ordinary wall impinging spray before its tip leaves the impinging part, but cannot grow downward (toward the wall). After the spray tip leaves the impinging part, the spray grows downward as well as in radial and upward directions. This is specific for the OSKA type spray.

From the bottom view observation indicated in the lower part of the figures, the spray spreads almost circularly before the injection ends, but its spreading shape turns into oval as the time passes after the injection.

<u>Effect of Injection Pressure</u>

Figure 7 shows histories of spray tip penetration length, $b$, at various nozzle opening pressures, $p_{FVO}$. From the figure, the spray tip penetration increases as the nozzle opening pressure and hence the discharging velocity increases. The effect of nozzle opening pressure on the spray tip penetration is not so large as expected from a simple model assuming that the spray thickness is constant with respect to the nozzle opening pressure,.

Figure 8 shows histories of spray thickness, $h_N$, against the injection nozzle and $h_W$, against the wall. The spray thickness, $h_N$, against the injection nozzle increases as the injection nozzle opening pressure increases during the injection period ($t < 0.64$ ms). The spray thickness, $h_W$, also increases and the effect of injection nozzle opening pressure is more significant after the injection ends than during the injection period.

The effect of injection nozzle opening pressure on the thickness, $h_N$, is significant during the injection period, because the injection pressure has great effects on rolling up motion of the spray tip as long as the momentum is supplied by the injection, so far as the Reynolds' number is not enough high to saturate the entrainment coefficient.

The effect of nozzle opening pressure on spray thickness, $h_W$, on the other hand, remains after the injection ends as well as the injection duration. The reason for this is that the negative pressure occurs between the spray lower surface and the wall due to entrainment, which depends on the injection pressure.

The negative pressure remains after the injection ends because surrounding gas has to flow through the narrow space between the spray lower surface and the wall to recover the pressure. As a result, the spray is attracted more when the injection pressure increases both during the injection period and after the injection ends.

The wall adhesion of the spray spoils the merit of the OSKA spray, that is, it entrains more air from both upper and lower surfaces. This results in poor combustion, resulting poor emission and performance characteristics.

These are the reason why the lower injection pressure is preferable at the OSKA combustion system.

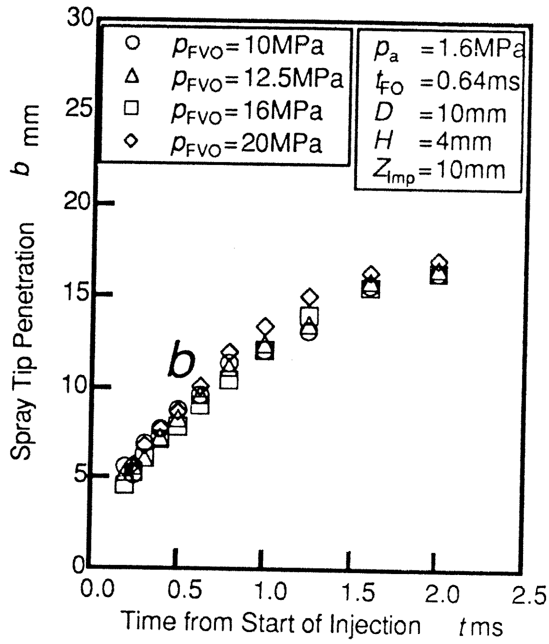


Fig. 7 History of Spray Tip Penetration Length, $b$, at Various Nozzle Opening Pressure, $p_{FVO}$

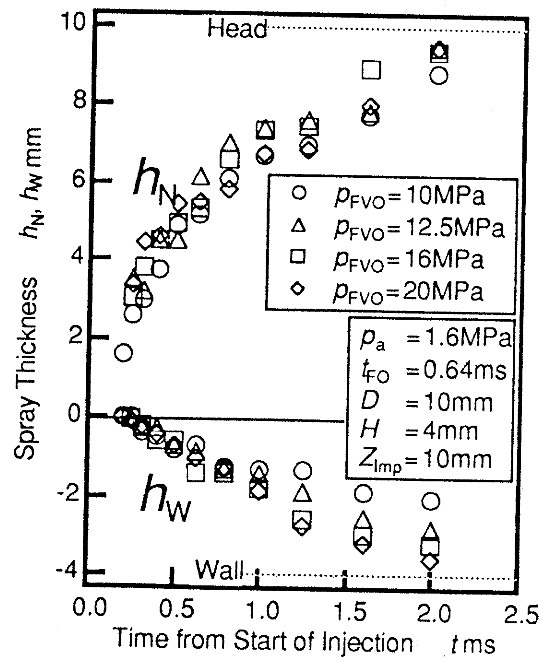


Fig. 8 History of Spray Thickness against Nozzle, $h_N$, and against Wall, $h_W$, at Various Nozzle Opening Pressure, $p_{FVO}$

Effect of Nozzle Needle Shape

Figure 9 shows a typical example of history of trajectories of the OSKA spray injected from a nozzle with a square needle.

The square needle forms an almost circular spray at first and then gradually turns to form square shaped spray, on the other hand, the ordinary needle forms a circular spray at first then forms oval one as described before.

The reason for this is that the flow area distribution between nozzle hole and needle is almost axially symmetric in the ordinary nozzle, but nonsymmetric in the square shaped needle equipped nozzle.

Smaller width across the flats of the needle, that means more square cut on the needle cylindrical surface, gives larger spray thickness and penetration under the same injection condition.

Figure 10 shows a history of spray tip penetration, $b$, injected from the nozzle with various widths, s, across flats of the square needle. The standard deviation, $\sigma_b$, of penetration is also plotted in the figure, which increases as the bottom view of the spray get nonuniform. Black marks in the figure denote those of the spray injected from the ordinary nozzle having the cylindrical needle as reference.

The spray injected from the nozzle has larger tip penetration than that injected from the ordinary nozzle with the cylindrical needle. The spray tip penetration gets larger as the width, $s$, across the flats of the square needle decreases, and vise versa. The reason for this is that the total area between the nozzle hole and the needle increases and the total injection momentum rises as the width across flats of the square needle

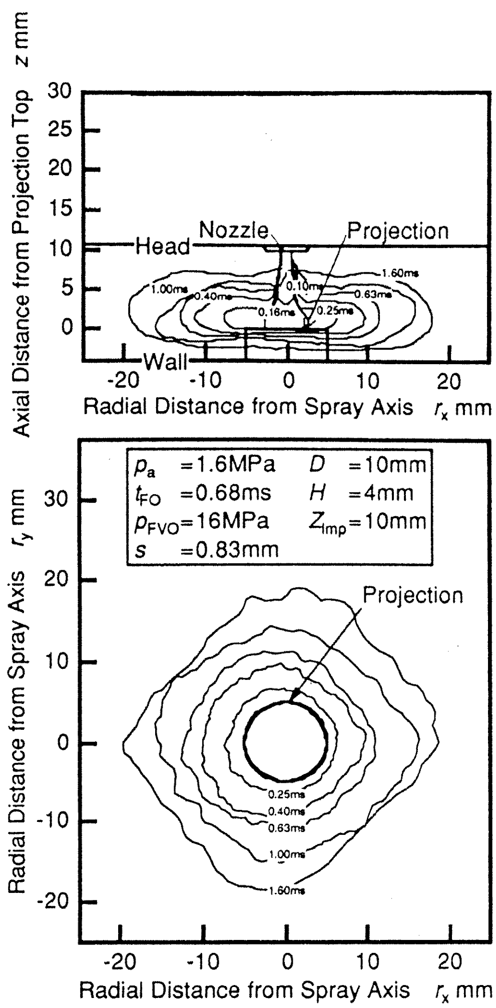


Fig.9 History of Spray Trajectories Injected from a Nozzle with Square Needle

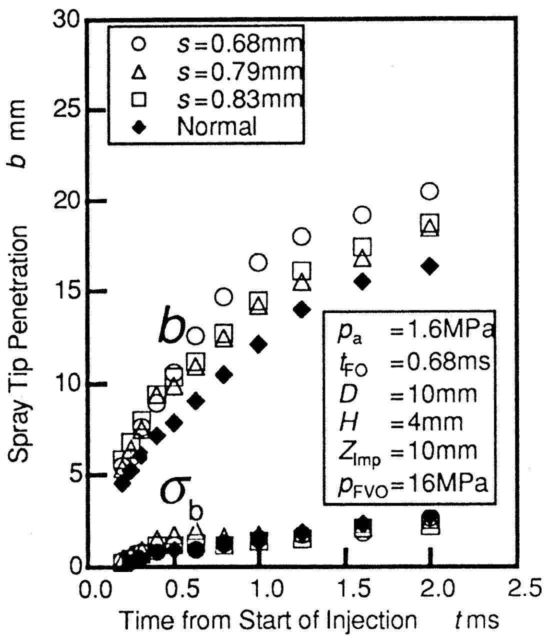


Fig. 10 History of Spray Tip Penetration Length, $b$, and Standard Deviation, $\sigma_b$, of Spray Injected from a Nozzle with Square Needle of Various Widths Across Flats, $s$, as well as with Normal one.

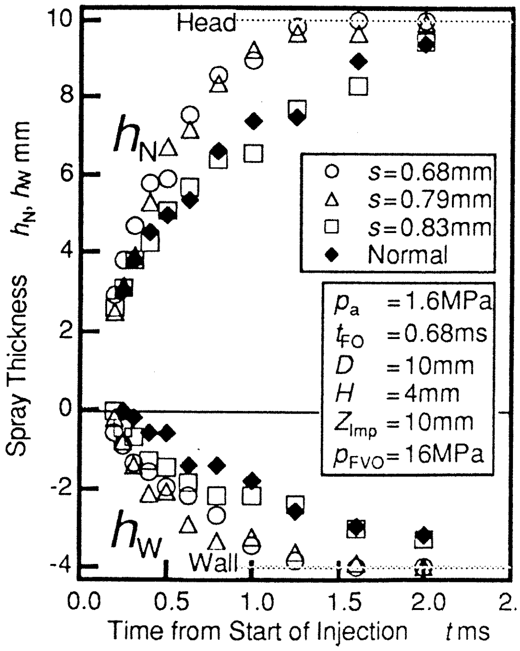


Fig. 11 History of Spray Thickness against Nozzle, $h_N$, and against Wall, $h_W$, Injected from a Nozzle with Square Needle of Various Widths Across Flats, $s$, as well as with Normal one.

decreases.

The standard deviation, $\sigma_b$, of the spray tip penetration is slightly higher, when the spray is injected from a square needled nozzle, than injected from an ordinary nozzle, within the injection period ($t$<0.63 ms). After the end of injection ($t$>0.63 ms), however, the standard deviation of penetration is almost identical regardless of the needle shape, because the bottom view shape becomes oval and distance from the spray axis gets nonuniform after the injection ends even in the spray injected from an ordinary nozzle with the cylindrical needle.

Figure 11 shows the history of spray thickness, against the injection nozzle, $h_N$, and that against the wall, $h_W$, injected from a nozzle with various widths, $s$, across the flats of needle.

Both the spray thickness against the injection nozzle and against the wall increases as the width across flats, $s$, of the square needle decreases. As the width,$s$, decreases the total injection momentum increases described above. This makes similar effects to that the injection pressure rises locally. Consequently, the square cut of the nozzle needle increases the spray thickness, resulting greater air entrainment.

## CONCLUSIONS

In order to clarify the characteristics of a spray impinging onto a surface on the wall as a fundamental study of the OSKA system, a photographic analysis was carried out using a pressure vessel. Following results are obtained:

1. Higher nozzle opening pressure increases the spray thickness as well as tip penetration length, resulting higher air entrainment.
2. Square cut of the needle of the injection nozzle increases spray thickness, as well as tip penetration.
3. Smaller width across the flats makes spray thickness and tip penetration larger.

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