技術論文

Analysis of Port Injected Fuel Spray Under Cross Wind Using 2-D Measurement Techniques

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要旨

二輪車用ガソリンエンジンには、ポート噴射システムが急速に広まりつつある。二輪車では自動車に比べ、インジェクタを設置する場所が制限されるため、燃料を吸気バルブへ直接噴射することが難しい。それに加え、スロットルが吸気ポートの直前に設置されるため、吸気ポート内の流速が非常に速い場所がある。また二輪車での課題として、サイクル変動が大きいことがある。どのようにインジェクタを設置しよい混合気を形成できるかは重要だが不明瞭である。この研究では、ILIDS(Interferometric Laser Imaging for Droplet Sizing)を使い、液滴の直径と速度・空間位置を同時計測し、噴射方向・流速・壁面粗さの混合気形成への影響をみた。これらをもとに、冷間始動・低中負荷・高負荷での影響を考察した。

Abstract

In a motorcycle gasoline engine, the port fuel injection system is rapidly spread. Compared to an automotive engine, the injected fuel does not impinge on the intake valve due to space restriction to install the injector. In addition, as the air flow inside the intake pipe may become very fast and has large cycle-to-cycle variation, it is not well found how the injector should be installed in the intake pipe to prepare "good" fuel-air mixture inside the intake pipe. In this study, the formation process of the fuel-air mixture is measured by using ILIDS system that is a 2-D droplets'size and velocity measurement system with high spatial resolution. Experiments with changing conditions such as flow speed and injection direction are carried out. As a result, the effects of injection direction, ambient flow speed and wall roughness on the fuel-air mixture formation process was examined, considering the three conditions of cold start, light to medium load operation and high load operation.

1 INTRODUCTION

The fuel supply system of a gasoline engine for motorcycles is getting common to use the port fuel injection system. This system is basically the same as of a passenger car, but due to the space restriction, the injected fuel does not impinge on the intake valve as the injector is located at upstream position. This difference may cause worse characteristics such as slow vaporization since the surface of intake valve is hot, long time response and also fuel attachment on the intake pipe wall while it does good characteristics such as high degree of freedom in injector installation. The worse characteristics may be recovered by optimizing the injector settings. For this process, numerical simulations are useful, but the accuracy is not evaluated and also detailed experimental study has been scarcely made[1].

Thereby, in this study, the spray characteristics injected upstream the intake valves are investigated by using a transparent duct to allow optical access. An improved ILIDS (Interferometric Laser Imaging for Droplet Sizing) method that can measure the velocity and diameter of spherical droplets on a plane, PDA (Phase Doppler Analysis) method that can measure the velocity and diameter of a spherical droplet in a small measurement volume and also laser tomography on a plane are applied. Experiments with changing conditions such as flow speed and injection direction are carried out using these techniques. As a result, the effects of injection direction, ambient flow speed and wall roughness on the fuel-air mixture formation process were examined, considering the three conditions of cold start, light to medium load operation and high load operation.

2 EXPERIMENTAL APPARATUS

MEASUREMENT DEVICE

Figure 1 shows the schematic of experimental apparatus including ILIDS optics. Details of ILIDS are already described in the author's previous papers[2-4]. An acrylic passage with a square cross-section of 20 x 20 mm was used. To make a flow inside the passage, a blower was installed with a laminar flow meter.

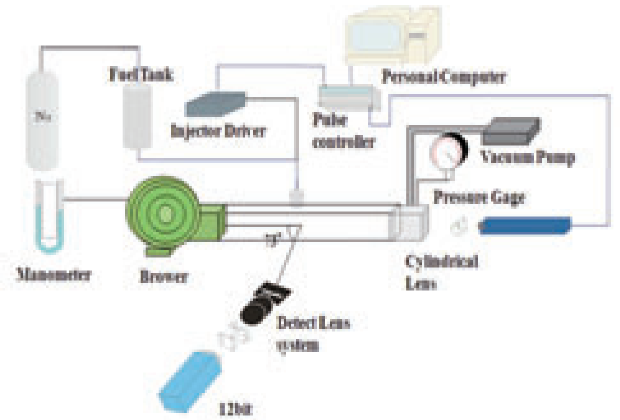


Fig. 1 Experimental apparatus of spray using ILIDS

A port fuel injector with four holes, spray angle of 5 degrees and volume flow rate of 145 cc/min was employed using n-heptane as a fuel and injection pressure was set at 0.3 MPa as a standard condition. The injection direction was changed from -60 to 60 degrees as illustrated in Fig. 2. Laser sheet was inserted into the passage from backward. The scattered light was detected with an angle of 73 degrees using a high speed video camera (Photoron FASTCAM APX-RS, 10 bit, 1024x1024, 3000 fps). As the laser source, a high-frequency double-pulse Nd-YLF laser (Newwave research, 527 nm, 10 mJ/pulse, 1500 double pulses/s) was used. PDA system (Dantec DualPDA) was also employed using an Ar-ion laser (488/514.5 nm, 4W) as shown in Fig. 3.

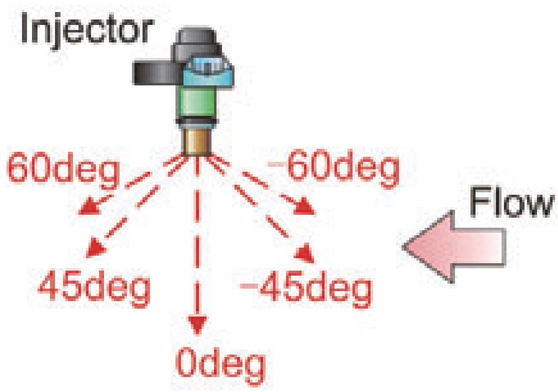


Fig. 2 Definition of injection direction to the flow

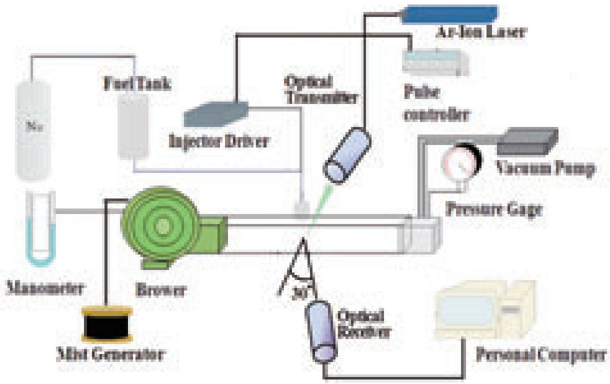


Fig. 3 Experimental apparatus of spray using PDA

PRELIMINARY MEASURED RESULTS

Figure 4 indicates the operation timing of devices. The first and second pulses of a double-pulsed laser are respectively defined as LASER1 and LASER2. The frame signal of the high-speed video camera was used as the standard clock.

The gas velocity inside the passage was measured using a 2D-LDV system along the passage and across the passage at the injector location. The measurement points are indicated in Fig. 5. The horizontal mean velocity at medium flow velocity condition is shown in Fig. 6. At each point, both the horizontal and vertical velocities were simultaneously measured. Along the passage, the mean horizontal velocity was almost constant around 55 m/s and the mean vertical velocity was almost zero. In both high and low flow velocity conditions, the speed was around 72 and 20 m/s, respectively. On the cross section, velocity was nearly homogeneous and the boundary layer thickness was found less than 2.5 mm.

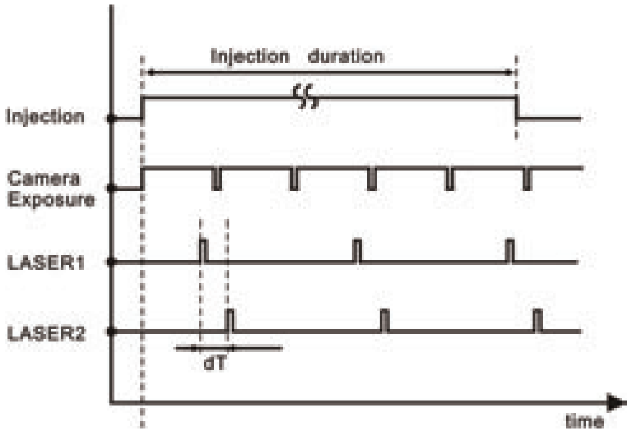


Fig. 4 Timing chart for experiments

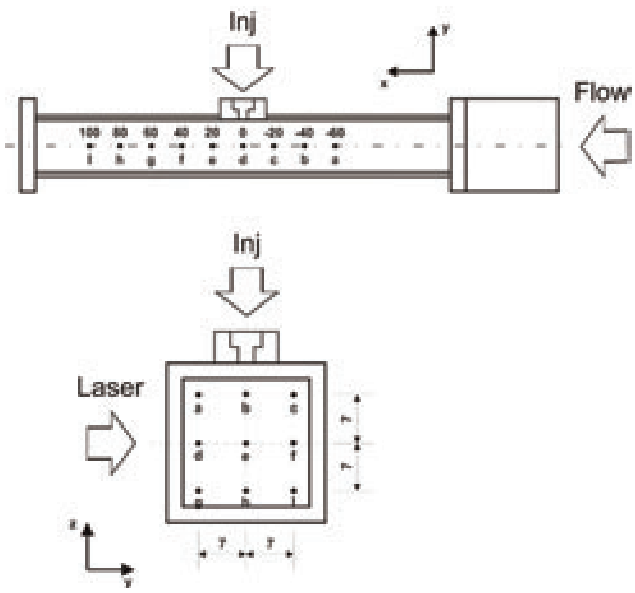


Fig. 5 LDV measurement locations

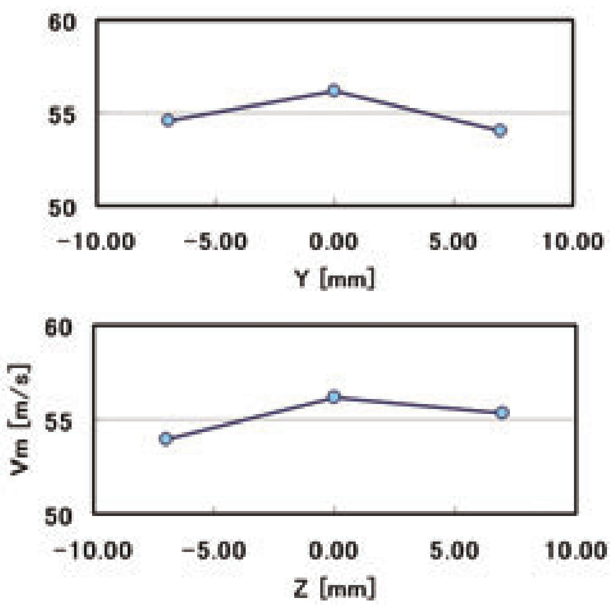


Fig. 6 LDV measured mean velocity

The spray characteristics in atmospheric condition were measured first. Two kinds of fuel (n-heptane and CCF) were used. The spray profile was taken by using a high-speed video camera in 10000 fps with 1/92000 s exposure time. The results are shown in Fig. 7. The diameter and velocity of droplets on a 2D area were measured using ILIDS system. The measurement was made with two injection pressures of 0.25 and 0.3 MPa.

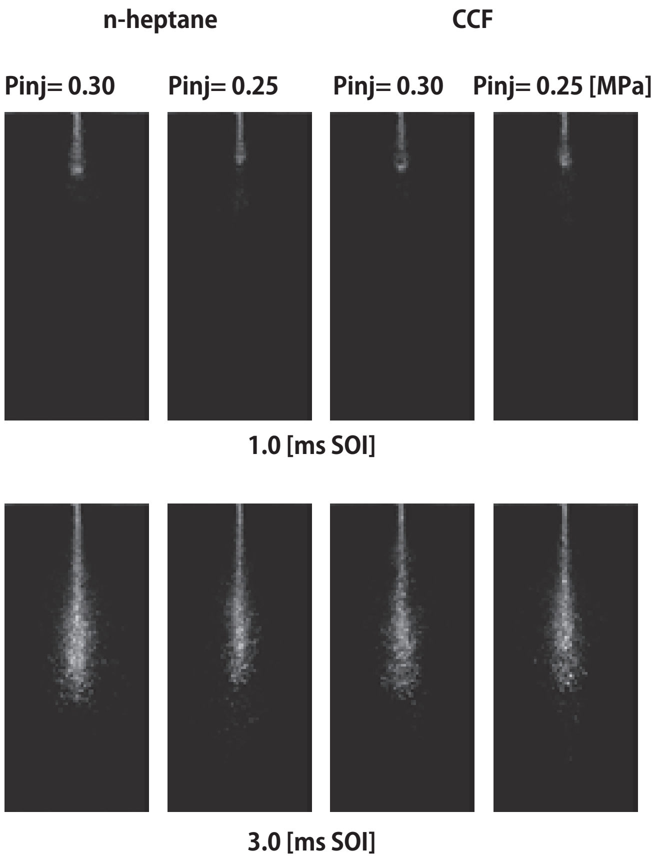


Fig. 7 High-speed photograph of spray for comparison of fuel and Injection pressure

The probability function of droplets diameter in number density and volume density are shown in Fig. 8. SMD (Sauter Mean Diameter) increases along the spray axis as only spherical droplets can be measured and ligament exits upstream. Figure 9 shows SMD values along the spray axis for both injection pressure of 0.25 and 0.3 MPa. CCF shows larger SMD values as its surface tension is larger than of n-heptane, leading to lower Weber number and breakup is suppressed.

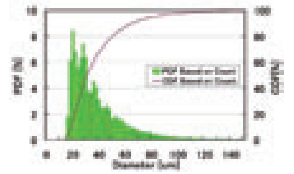
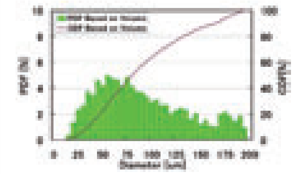
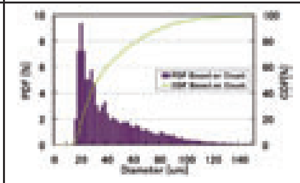
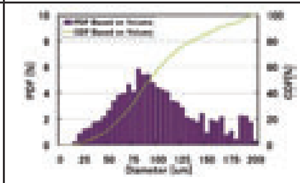
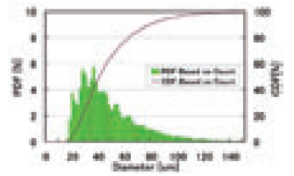
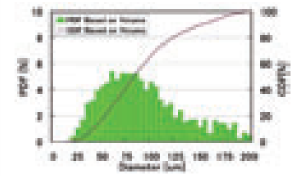
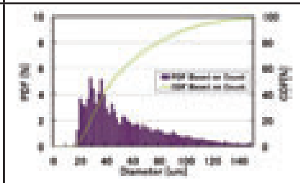
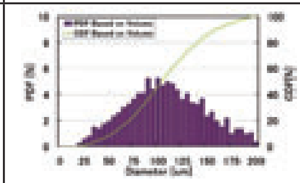
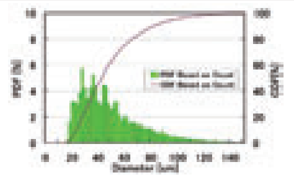
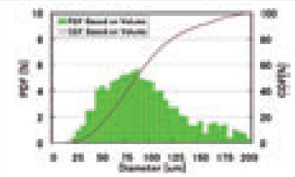
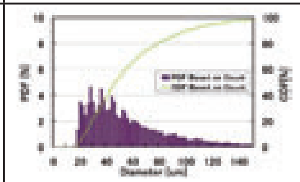
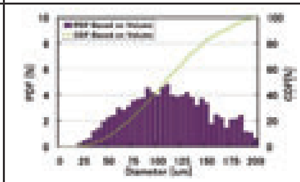
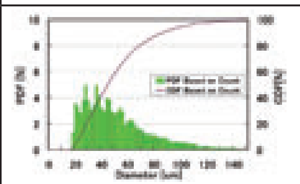
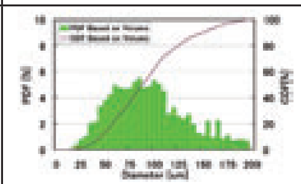
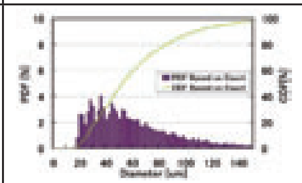
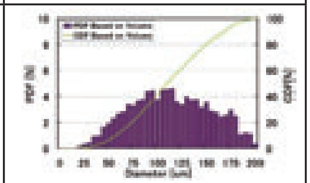
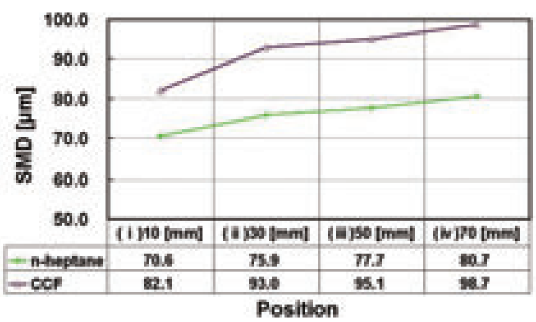
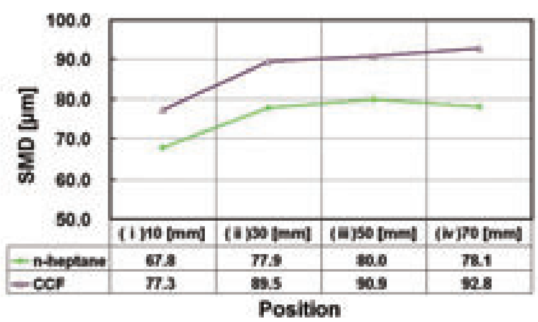
	n-heptane		CCF	
	PDF Based on Number of Droplets	PDF Based on Volume of Droplets	PDF Based on Number of Droplets	PDF Based on Volume of Droplets
(i) 10 [mm]				
	SMD=70.6 [um]		SMD=82.1 [um]	
(ii) 30 [mm]				
	SMD=75.9 [um]		SMD=93.0 [um]	
(iii) 50 [mm]				
	SMD=77.7 [um]		SMD=95.1 [um]	
(iv) 70 [mm]				
	SMD=80.7 [um]		SMD=98.7 [um]	

Fig. 8 Probability density function of droplet diameter distribution with injection pressure of 0.25 MPa



Injection pressure: 0.25 MPa



Injection pressure: 0.3 MPa

Fig. 9 SMD values along the spray axis

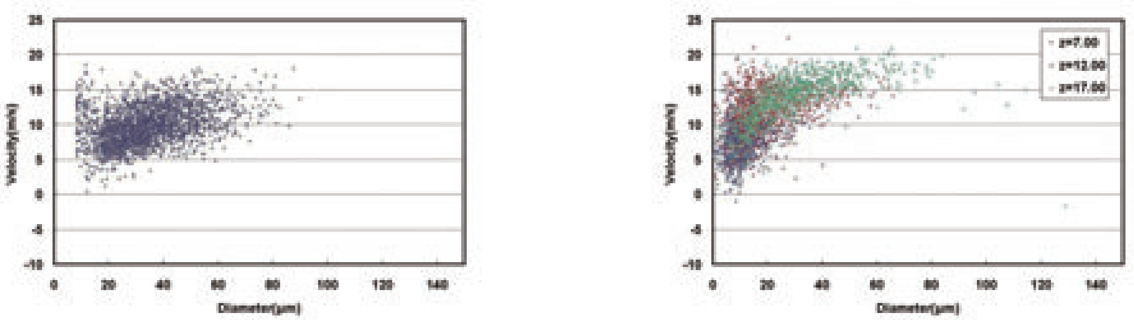


Fig. 10 Comparison of ILIDS (left) and PDA (right) results

FEATURES OF ILIDS

ILIDS has features of simultaneous measurement of every droplet on 2-D plane while the measurement limit of small droplet size is around 10 μm and measurement is difficult in a dense spray. Thereby, the spatial resolution is better than of PDA while temporal resolution is not so good as of PDA. However, as ILIDS can detect instantaneous spray characteristics that cannot be realized by PDA, it is favorable to see the cycle-to-cycle variation of spray.

Figure 10 shows a comparison of correlation of droplet diameter and velocity between ILIDS and PDA near the spray tip in a quiescent condition shown in lower Fig. 7. Because ILIDS has a wide measurement area of 10 x 10 mm, PDA was carried out at three points and all results are plotted together. Except for the difference in small droplet region, the profile is similar to each other. This is probably due to that small droplets easily follow to the ambient flow which causes cycle-to-cycle variation of spray and that small droplets less than 10 μm cannot be detected by ILIDS. Thereby, ILIDS is convenient to see the area-averaged information.

3 RESULTS AND DISCUSSION OF SPRAY WITH CROSS WIND

ILIDS MEASUREMENT

Figure 11 shows tomograms of spray in different injection directions and ambient flow speeds of 20 and 72 m/s. Figure 12 shows the temporal variations of SMD in area (a) near injector. Area (a) is 10 x 10 mm and the center is located at X = -10 mm, Z = 5 mm. X axis is along the flow and its zero position is the injection position. Z axis is vertical direction and its zero position is also the injection position.

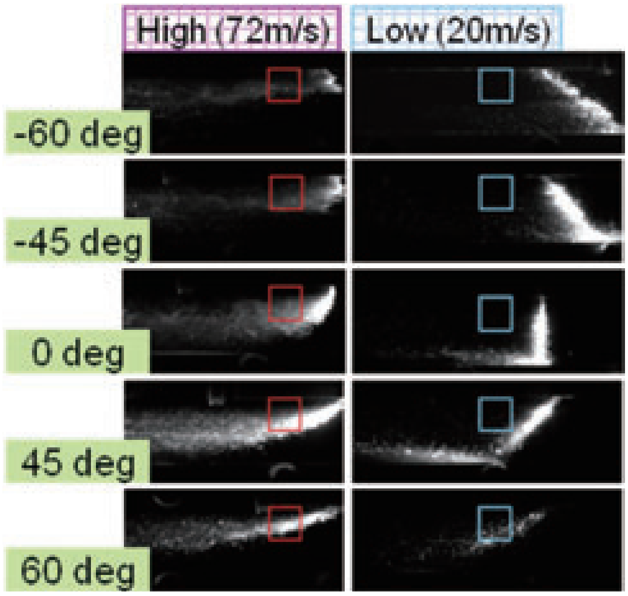


Fig. 11 Spray tomograms of different flow speeds and injection directions
(Square area indicates area (a))

With injection directions of 45 or 60 degrees, SMD shows smaller values with high ambient flow than with low ambient flow. For this reason, secondary breakup is enhanced in high flow conditions as Weber number, defined by Eq.(1), becomes large as the relative velocity between droplets and ambient gas is large in these conditions[5].

$$We = \frac{\rho_g \Delta V^2 d}{\sigma} \qquad (1)$$

Here, ρ_g is gas density, ΔV relative velocity between droplet and ambient gas and σ surface tension.

With injection directions of -45 or -60 degrees, SMD shows larger values with high ambient flow than with low

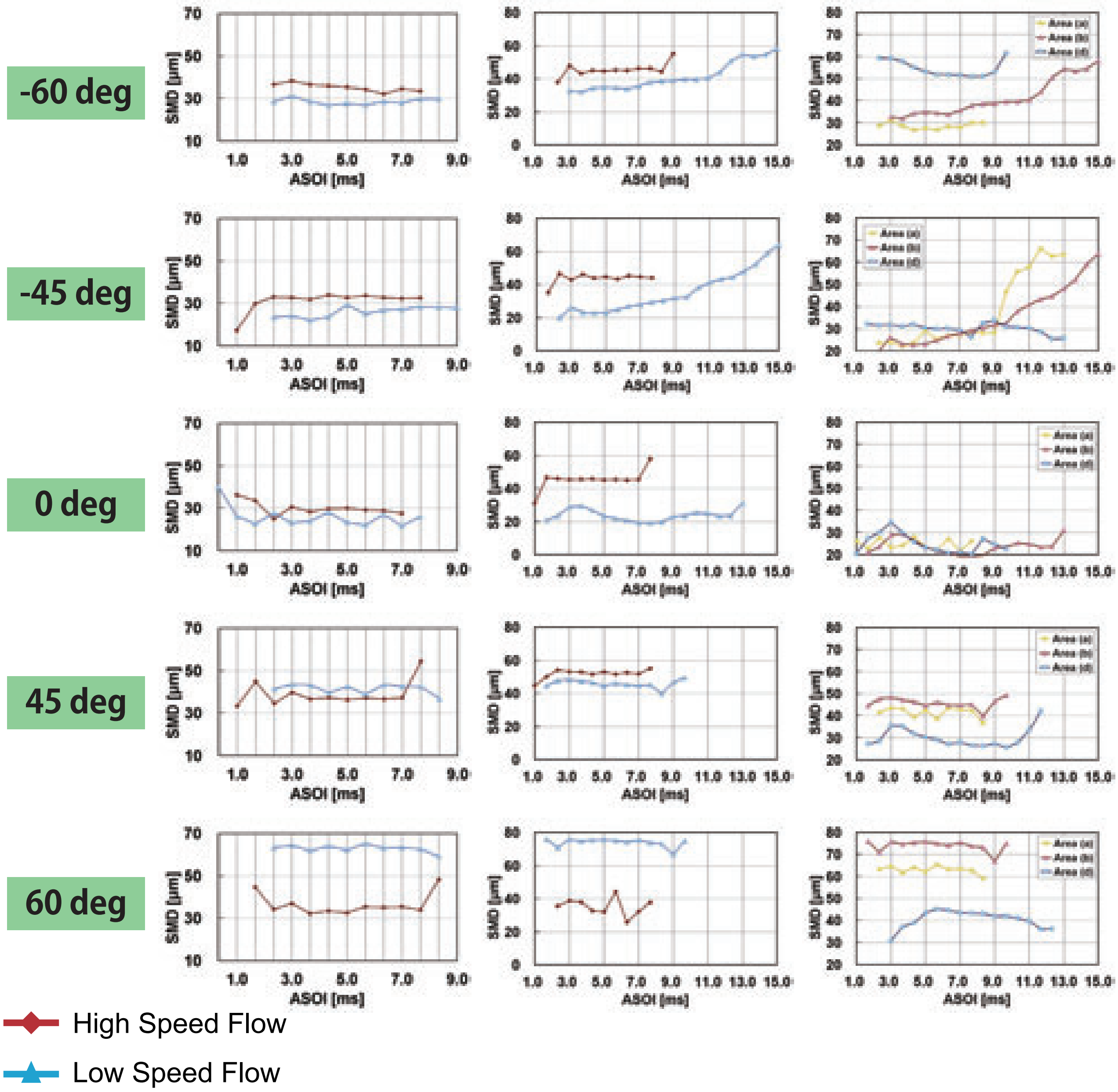


Fig. 12 Temporal variation of SMD values in area (a) for diffeent conditions

Fig. 13 Temporal variations of SMD in area (b) near injector and near lower wall

Fig. 14 Comparison of SMD among three areas with low ambient flow condition.

ambient flow. For this reason, the effect of classification brings larger droplets to this area. To see the effect of classification, Fig 15 shows the diameter distribution of droplets in each measurement area. In this figure, three graphs are shown in each injection direction; left-top is a tomogram of the spray, left-down shows locally averaged SMD value along the vertical (Z) axis, and right-down shows droplet diameter distribution in the measurement area where each diameter of circle indicates the local droplet diameter. A strong classification can be found in the condition of high speed flow with injection direction of 0 and 60 degrees. ILIDS has such a feature to show droplet diameter distribution in an area and then, it is very useful to see the effect of interference of droplets motion (ILIDS also measures each droplet's velocity).

Figure 13 shows the temporal variations of SMD in area (b) near injector and near lower wall. (X = -10 mm, Z = 15 mm) Except for injection direction of 60 degrees, SMD

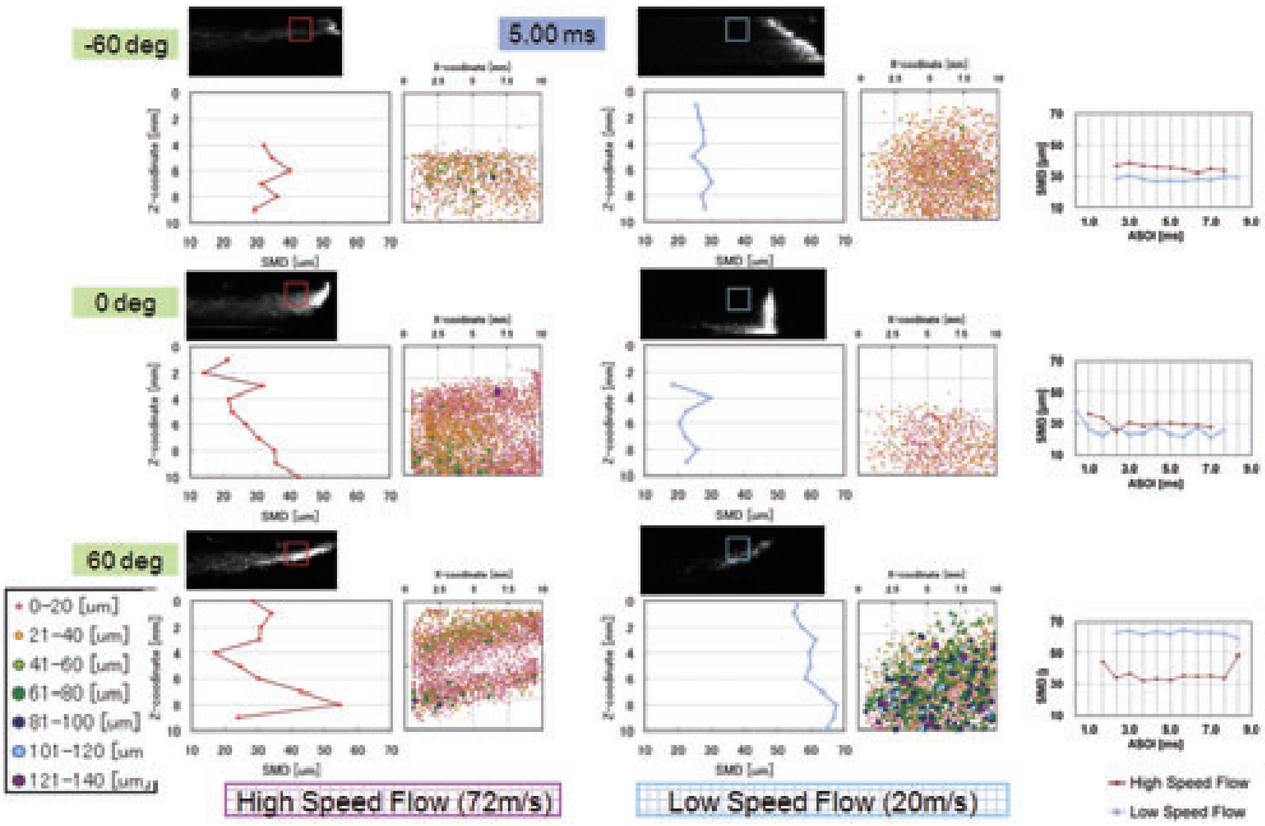


Fig. 15 Diameter distribution of droplets in each measurement area at different conditions (left-top: tomogram of the spray, left-down: locally averaged SMD value along Z axis, right-down: droplet diameter distribution in each area where each circle's size indicates droplet's size)

shows smaller values with low ambient flow than with high ambient flow that is different to the result of area (a). Seeing the tomogram, much spray droplets impinge onto the lower wall with low speed flow. Thereby, droplet breakup is enhanced by the impingement and this is quite effective for low speed conditions.

Figure 16 shows temporal variations of droplets diameter distribution in area (b) with injection angle of -60 degrees. As time elapses, the probability of small droplet around 20 μm reduces while that of large droplet increases. This means that large droplets come in the area with delayed time.

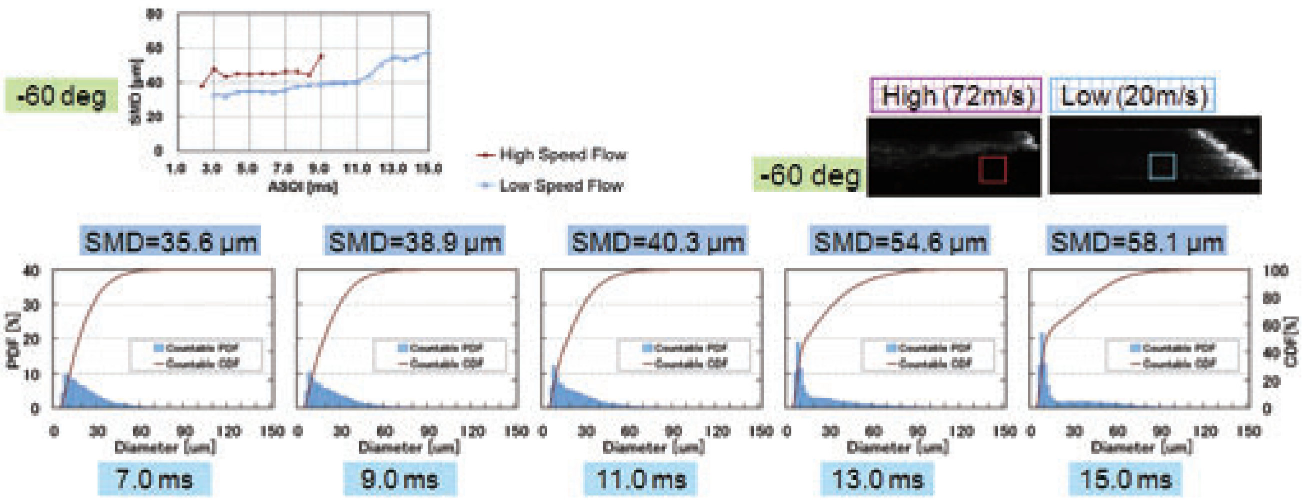


Fig. 16 Temporal variations of droplet diameter distribution in area (b) with injection direction of -60 degrees

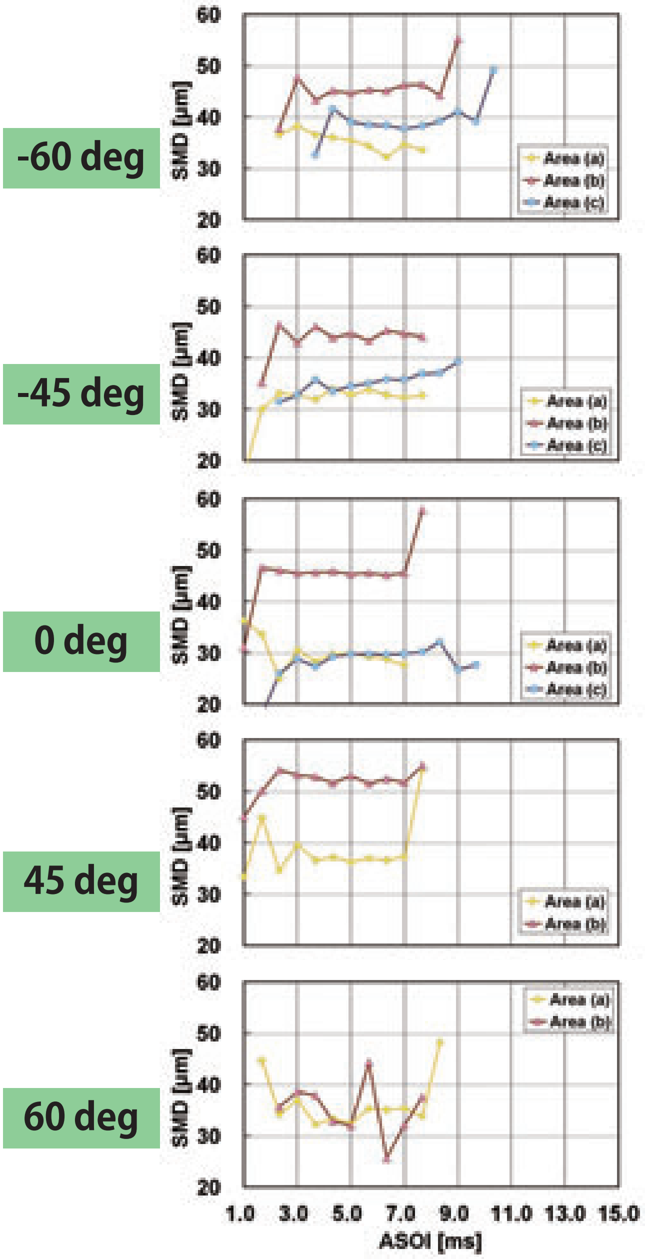


Fig. 17 Difference of SMD value among areas of (a), (b) and (c) in high ambient flow conditions

Here, the difference of SMD value in measurement areas of (a), (b) and (d) is examined. Area (d) is not a fixed position, but the location is just advanced where spray impinges. Figure 14 shows the comparison among the three areas with low ambient flow. With injection directions of -60 and -45 degrees, SMD of area (d) shows the largest due to the classification effect while with 45 and 60 degrees, it shows the smallest due to the wall impingement effect.

Figure 17 shows the difference of SMD value in the measurement areas of (a), (b) and (c) at high ambient flow conditions. The area (c) is not a fixed position, but the location is far away from the nozzle. As a result, SMD of area (a), (c) and (b) almost increases in the order.

Next, the difference of ambient flow was examined at area (a) in Fig. 18. With injection directions of -60 and 0 degrees, SMD distribution with high ambient flow is wider than with low flow as most droplets pass into this area. Meanwhile, droplet size distribution with low ambient flow is not so wide as larger droplets concentrate near the lower wall due to the classification

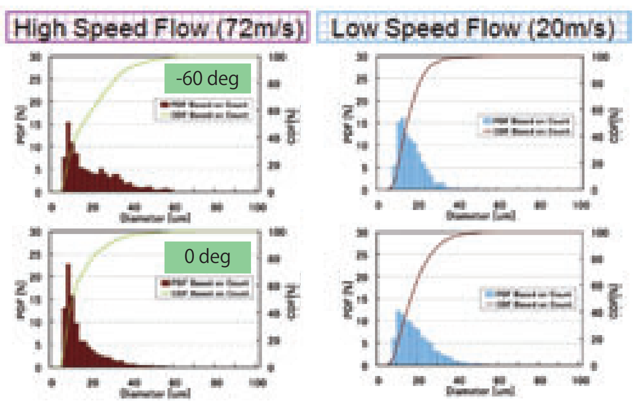


Fig. 18 Effect of ambient flow on droplet size distribution at area (a)

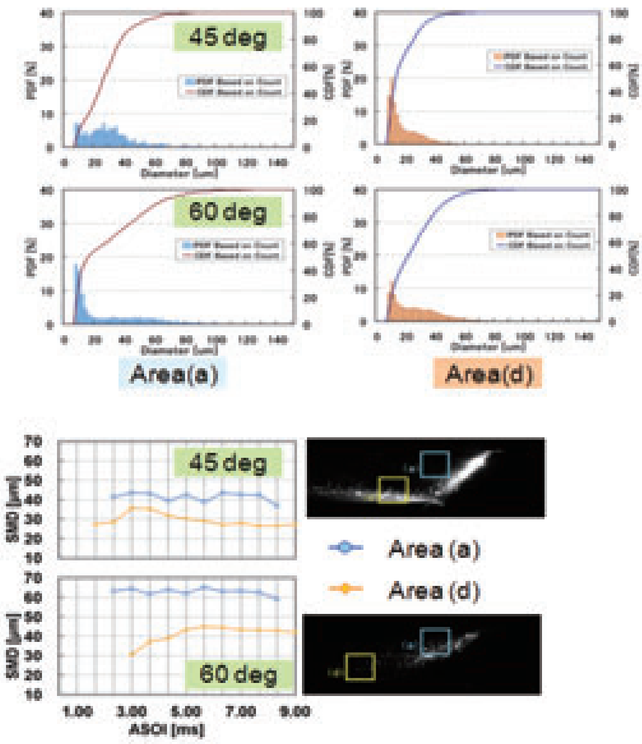


Fig. 19 Droplets size distribution in low ambient flow with injection directions of 45 and 60 degrees at areas (a) and (d)

and do not pass into this area.

Figure 19 shows droplets size distribution in low ambient flow with injection directions of 45 and 60 degrees at areas of (a) and (d). In area (d), large droplet part disappears because wall impingement enhances droplet breakup.

WALL ROUGHNESS EFFECT

The effect of wall roughness was examined by changing a smooth plate to a rough plate of the lower wall. Figure 20 shows the temporal variation of SMD value in area (c) ambient flow. Slightly smaller SMD was found with rough wall. This means that some droplets must impinge on the wall and breakup occurs or big droplets attach on the wall.

Figure 21 shows results in area (d) with low ambient flow. Except for the injection direction of -60 degrees, much difference in SMD was not found. It is interesting that although wall impingement is certainly affective in low ambient speed conditions, the wall roughness seems not so affective. For this reason, according to the tomogram, most droplets seem not to impinge on and reflect from the wall because scattering light is not observed. This causes many droplets to attach on the wall, especially for rough surface wall.

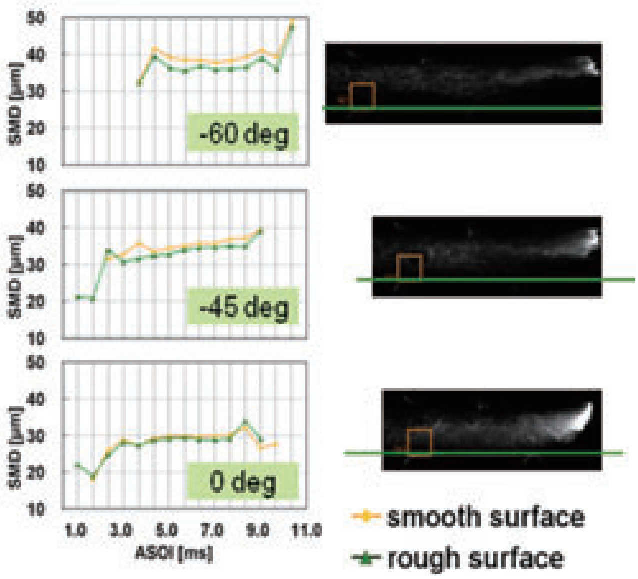


Fig. 20 Temporal variation of SMD value in area (c) with high ambient flow

OPTIMIZED INJECTOR SETTINGS

The role of spray characteristics changes depending on the engine status. Here, cold start, light to medium load operation and high load condition are examined. At cold start state, a preparation of homogeneously well vaporized fuel-air mixture is required. To achieve this, atomization is quite important as small droplets have large surface area and enhance vaporization. Above results show that the injection direction, ambient flow velocity and wall impingement affect the atomization. At cold start condition, as the engine load is not so high, the flow velocity is low. Thereby, atomization can be enhanced by wall impingement, especially with injection direction around 0 degree. Increasing the injection degree may cause worse atomization.

At light to medium load operation, response to the demand is important. The flow velocity changes between low and high velocity. Fuel response is good with injection direction at around +60 degrees.

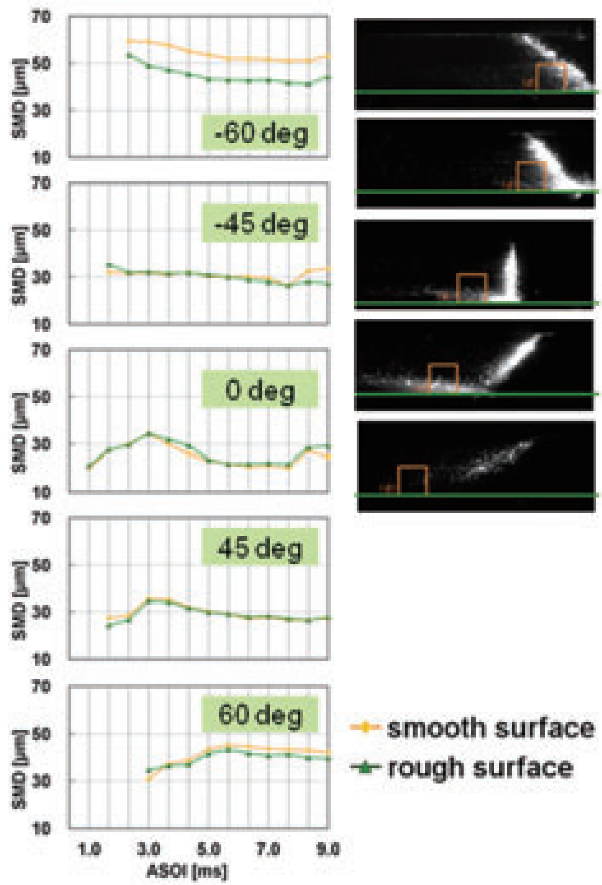


Fig. 21 Temporal variation of SMD value in area (d) with low ambient flow

At high load condition, control of knocking is very important. Thereby, homogeneous mixture and cooled mixture are favorable. In this condition, as the flow velocity is high and turbulence diffusivity is also high, fuel should be injected following the flow with injection direction around +45 degrees. Atomization need not be enhanced because introducing large fuel droplets into the cylinder can reduce the mixture temperature during compression stroke due to the vaporization heat supplied by the ambient in-cylinder gas. Meanwhile, when fuel is injected against the flow direction with minus injection degrees, the atomization is much enhanced. To reduce knocking, preparing homogeneous fuel-air mixture is required. Thereby, the appropriate injection angle should be determined by performing engine performance tests.
As a result, when only one injector is used, the injection direction should be set around +45 degrees to cover the above three conditions. However, if two injectors are available, one injector for low load should be set at 0 degree while the other one for high load may be set at +60 or -60 degrees, depending on the knocking tolerance.

4 CONCLUSIONS

In order to measure the spray characteristics, such as the diameter and velocity of each droplet in a 2D area simultaneously, an improved ILIDS method was applied to a spray using a square duct, simulating an intake pipe of a motorcycle port fuel injection engine. ILIDS method was found convenient to see the area-averaged information whereas information on small droplets less than 10 μm is not available. The measured data are useful to evaluate the numerical simulation models. Also, experimental analyses deduced the following conclusions.

(1) When the ambient flow speed is high, most droplets of a spray do not impinge on the wall, but when the flow speed is low, some or most droplets impinge on the wall and then being convected by the flow. This difference causes different atomization characteristics at the intake port far downstream.

(2) In the upstream region, due to the difference of the locally relative velocity between the ambient flow and the droplet, when the injection is made to the same direction of the flow, SMD of droplets becomes small with high flow velocity compared to with low flow velocity. Moreover, SMD takes large value with high ambient flow when the injection is made to the same direction compared to the opposite direction conditions. Meanwhile, when the injection is made to the opposite direction, SMD takes large value with a high ambient flow compared to with a low flow due to the effect of classification.

(3) In the downstream region, the droplet size shows smaller value when the flow velocity is low. This is probably due to that the effect of wall impingement is more dominant than of breakup by the ambient flow. Meanwhile, when fuel is injected against the flow, SMD becomes large with time.

(4) The effect of wall impingement was examined using different surface roughness plates. As a result, a rough wall showed slightly enhanced atomization in most conditions. For this reason, breakup is enhanced by the impingement and also big droplets adhere on the wall. When the flow is slow, a large difference in SMD was found at injection direction of -60 degrees.

(5) Through the whole study, when only one injector is used, the injection direction should be set around +45 degrees to cover the three conditions of cold start, light to medium load operation and high load operation. However, if two injectors are available, one injector for low load should be set at 0 degree while the other one for high load may be set at +60 or -60 degrees, depending on the knocking tolerance.

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