Effect of Wall Impingement on the Atomization Characteristics of an Air-Blasting Nozzle for Jet Engines

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Abstract

This paper presents the effect of applying pressure atomization with wall impingement on the atomization characteristics of air-blasting nozzle for jet engines. A real size air-blasting burner was installed in a test rig where three thin holes were made for liquid injection toward the intermediate ring as an impingement wall. The air velocity was varied from 41 to 92 m/s and the liquid injection pressure was from 0.5 MPa to 7.5 MPa. The atomization characteristics were evaluated by droplet size and velocity by using phase Doppler anemometry and light scattering sizing. Combining the pressure atomization with gas-blasting gives remarkable improvement of atomization, which comes from the contribution of droplets produced by pressure atomization mode. Comparison with the previous formulation for the conventional gas-blasting atomization is also made and the effectiveness of utilizing pressure atomization is shown.

1. Introduction

NOx in stratosphere is considered to cause serious damage to Ozone layer, and the 60 % of NOx emission in such high sky comes from airplane. Therefore the need of NOx reduction from airplane engines is increasing. A common procedure of NOx reduction in jet engines is pre-vaporized and pre-mixed combustion at lean condition. In order to achieve such lean premixed combustion, the improvement of atomization characteristics of a burner is necessary. In current jet engines, so-called air-blasting nozzle is widely used due to its highly homogeneous fuel distribution leading to little soot emission even at high load. However it has a problem of poor atomization at low load, since the atomization is determined by the relative velocity between air stream and liquid film. Furthermore, the SMD (Sauter Mean Diameter) range of such air-blasting nozzle is in 50 to 300 um which is not sufficient for realizing premixed lean combustion.

On the basis of this background, the authors propose a concept of combining the air-blasting atomization with pressure atomization utilizing wall impingement. In this study, in a real scale burner the atomization characteristics were evaluated under atmospheric condition, and the effectiveness of such combination of atomization regimes is shown.

2. Experimental Setup and Procedure

Schematic of experimental setup is shown in Fig. 1. A real size burner was installed at the exit of a capacity chamber through which air was supplied from a blower. The pressure detected by a manometer was used to represent the air flow rate, and the air velocity was estimated from the static pressure at the chamber. The air flow rate was controlled by the by-pass valve installed just upstream of the chamber.

Pure water was used as a test liquid. It was pressurized with bomb N_2 gas bottle in a pressure vessel, and was directly supplied to the atomizer. The atomization characteristics were evaluated on the basis of the droplet size and the velocity of the droplets using two kinds of facilities, designated LDSA (narrow-angle forward-scattering principle, Toh-nichi Computer Applications Co., LDSA-1300 A) and PDPA (Phase Doppler Anemometry, Aerometrics Co., PDPA-100).

A real scale burner is shown in Fig. 2. It has two swirlers for air streams which produce reverse direction swirls between inside and outside coaxial air flows. Liquid was supplied from hole-type nozzles at part A in the central part named spindle. The liquid jet emerges through the holes and possibly impinges the wall close to the lip end of intermediate ring. The

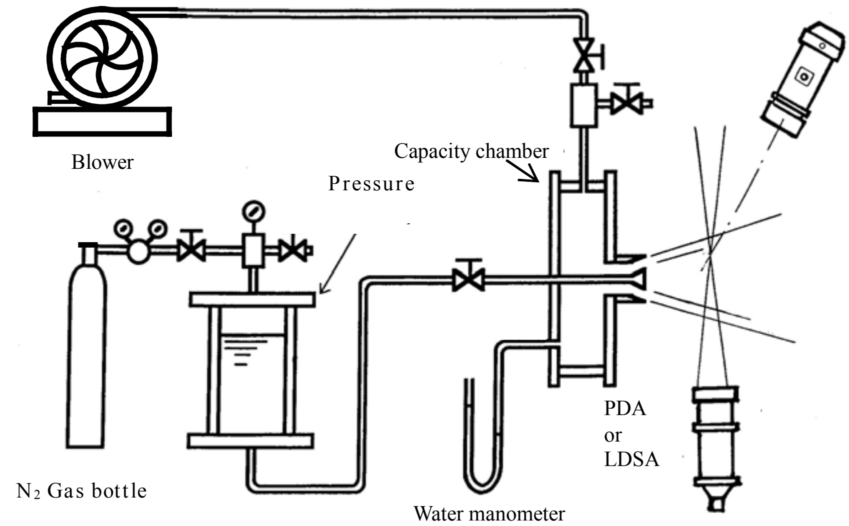
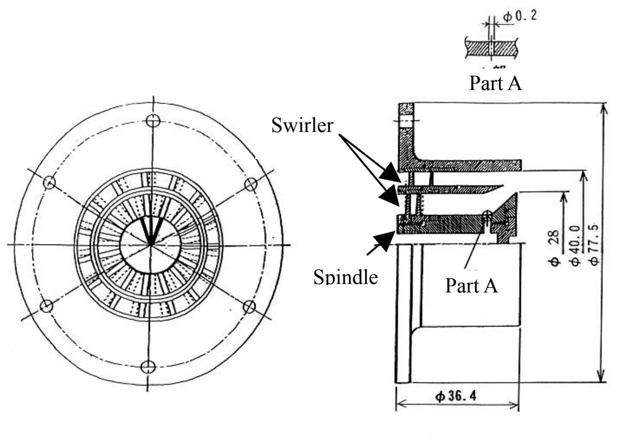


Fig.1 Schematic of experimental setup.



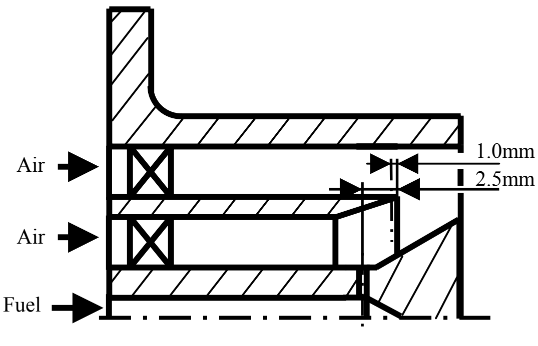


Fig.2 Real scale burner tested.

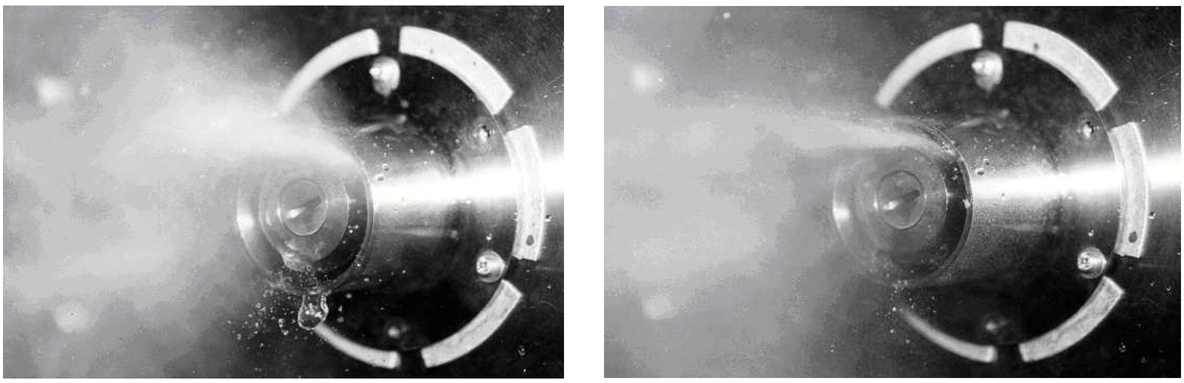
Fig.3 Cross-sectional view of burner.

detail of the part of hole-type nozzles and the lip is shown in Fig. 3. The expected impinging points were set at two positions by adjusting the intermediate ring, 2.5 mm and 1.0 mm upstream of the lip end. This must give the result of the effect of the impingement position. The diameter of the hole was 0.2 mm, and three holes were made with 20 deg spacing. According to the preliminary experiment, the discharge coefficient of these holes was constant at 0.62 in the liquid injection pressure range from 0.5 to 7.5 MPa, and it increased to 0.8 when the liquid injection pressure was decreased to less than 0.2 MPa. This indicates that the liquid flow inside the nozzle is contracted when the liquid injection pressure was greater than 0.5 MPa, since almost comparable value of discharge coefficient was obtained in the authors' study for a simple hole nozzle [1].

3. Results and Discussions

3.1 Photographic observation

Direct photographs taken by a strobo-light are shown in Fig. 4. This is the case of the highest liquid injection pressure of 7.5 MPa. Regardless the air velocity, finely atomized droplets are observed. However, especially for lower air velocity, bulky liquids are formed with poor atomization. Since the hole nozzles are installed at upper part, these bulky liquids would come from the reattached liquid to the walls. At this injection pressure of 7.5 MPa, it is hard to see if the atomization is determined by air velocity or liquid injection pressure.



(a) (b)

Fig.4 Direct photographs of atomization , liquid injection pressure = 7.5 MPa ,
(a) Air velocity = 41 m/s , (b) 71 m/s.

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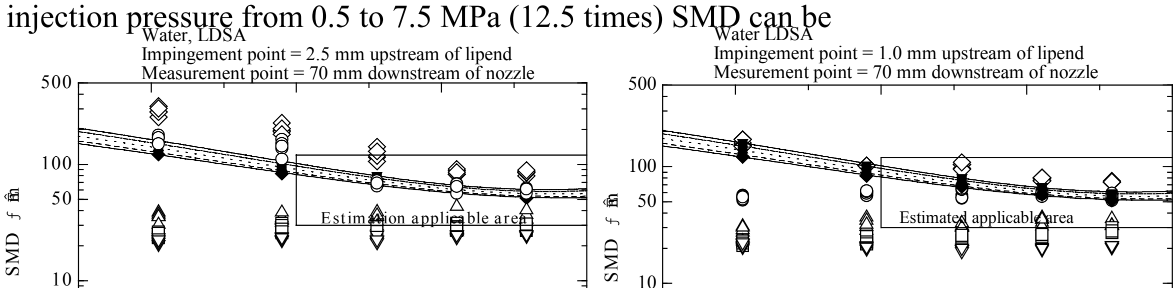
3.2 Effect of liquid injection pressure on SMD

In Fig. 5, SMD obtained by LDSA is shown against the air velocity together with the effect of liquid injection pressure and the impingement position. For both cases of impingement positions, at lower liquid injection pressure SMD decreases with the increase in air velocity, and at higher liquid injection pressure SMD varies little with air velocity. In terms of the effect of air velocity, there are two typical behaviors of SMD, and it shows that air velocity is no more effective factor for the liquid atomization at the condition of higher liquid injection pressure.
As for the effect of liquid injection pressure, it gives remarkable improvement of atomization especially at lower air velocity. At the impingement position of 2.5 mm, by increasing the liquid injection pressure from 0.5 to 7.5 MPa (12.5 times) SMD can be



decreased from 300 um to 21 um (1/14.3) at the air velocity of 41 m/s, and it is from 90 um to 25 um (1/3.6) at 71 m/s. Thus it is clearly shown that applying pressure atomization with wall impingement is effective to promote liquid atomization especially at lower air velocity. This must be great benefit for application, since one problem for air-blasting nozzle is the poor atomization at lower air velocity as mentioned before. Furthermore for both cases of impingement position, SMD decrease becomes less at the injection pressure greater than 2.5 MPa. In Table I and II, the ratio of each parameter is summarized at the liquid injection pressure of this condition. Since in the previous study it was shown that SMD is decreased proportionally to the increase in the liquid injection velocity at the nozzle exit for free jet [1], the liquid injection velocity was obtained as the potential velocity of the liquid injection pressure. In all cases, the ratio of SMD is less than that of liquid injection velocity. This is different from the behavior of SMD in free jet atomization. A basic approach for the atomization of liquid jet with wall impingement is discussed in the authors' report, and this dependence of SMD on the liquid injection pressure seems to be reasonable [2].

Table□. Variation of SMD with the inj. press. and correspoding inj. vel., and those ratios of variation.(2.5 mm, 70 mm downstream of nozzle).

Inj. Press.		Inj. Vel. (from Inj.Press)		SMD	
[MPa]	Ratio	[m/s]	Ratio	[μm]	Ratio
2.5	2	70.7	1.414	26~43	1.2
5.0		100.0		23~31	
7.5	1.5	122.5	1.225	21~25	1.2

Table□. Variation of SMD with the inj. press. and correspoding inj. vel., and those ratios of variation.(1.0 mm, 70 mm downstream of nozzle).

Inj. Press.		Inj. Vel. (from Inj.Press)		SMD	
[MPa]	Ratio	[m/s]	Ratio	[μm]	Ratio
2.5	2	70.7	1.414	23~36	1.3
5.0		100.0		22~30	
7.5	1.5	122.5	1.225	19~22	1.2

Let us back to the SMD behavior in Fig. 5, where the estimation by Rizkalla and Lefebvre is indicated. They derived an empirical equation for conventional air-blasting (prefilming) atomizer [3].

$$\mathrm{SMD} = 3.33\times10^{-3}\frac{(\sigma\rho_L D_p)^{0.5}}{\rho_A U_A}\left(1+\frac{1}{\mathrm{ALR}}\right)+13.0\times10^{-3}\left(\frac{{\mu_L}^2}{\sigma\rho_L}\right)^{0.425} {D_p}^{0.575}\left(1+\frac{1}{\mathrm{ALR}}\right)^2$$

where

σ; surface tension [kg/s^2] ρ;density [kg/m^3]μ;viscosity [kg/m□s]
U_A; air velotiy [m/s] D_p ;outside diameter of lip [m]
ALR; ratio of flow rate of air to liquid
Subscript; A=air, L=liquid.

The applicable range of this formulation is as follows.

σ_L; 24~73×10^{-3} [kg/s^2] ρ_L; 780~1500 [kg/m^3]
μ_L ;1.0~44×10^{-3} [kg/m□s] P_A; 1.0~8.5×10^{-2} [Pa]
T_A; 296~424 [K] U_A; 70~125 [m/s]
ALR; 2~11 SMD; 30~120 [μm]

In the figure, dark symbols with the corresponding lines were obtained by taking the experimental condition of this study into the equation. The area designated as "Estimation applicable area" is the region to which the equation can be adopted.

At the liquid injection pressure of 0.5 MPa (mass flow rate of 1.87 g/s), SMD for 2.5 mm impingement position is rather greater than the value estimated by the equation, while it gives better agreement for the 1.0 mm impingement position. Considering that in Rizkalla and Lefebvre's experiment liquid was supplied with minimum impingement velocity to form liquid film along the wall, this may be due to the effect of wall impingement. In this study, liquid was supplied as a liquid column through thin holes and was impinged to the wall with its potential velocity corresponding to the liquid injection pressure. Thus at the lowest liquid injection pressure of 0.5 MPa, when liquid impinges close to the lip end almost the same atomization occurs as that in conventional prefilming atomization mode, while when the impingement position is upstream of the lip end the atomization is suppressed probably due to the increase in the liquid film thickness at the lip end.

At the liquid injection pressure of 1 MPa (mass flow rate of 2.63 g/s), in lower air velocity region SMD for 2.5 mm impingement is greater than that for 1.0 mm, and in higher air velocity SMD for both cases approaches the same value which is consistent with that of the estimation. Thus when air velocity is lower SMD is quite sensitive to the impingement position. For 2.5 mm impingement SMD would be still affected by the droplets produced by air-blasting mode, while for 1.0 mm impingement droplets produced by pressure atomization with wall impingement would be dominant due to small distance from the lip end. When air velocity is higher, effect of pressure atomization would have been overcome by the contribution of air-blasting mode due to the high velocity of air stream.

At the liquid injection pressure higher than 2.5 MPa, SMD is much less than the estimation regardless the air velocity, which must be due to the contributin of pressure atomization with wall impingement as mentioned in the discussion of SMD dependence on the liquid injection pressure.

SMD is expressed by conventional parameter of air to liquid ratio ALR in Fig. 6. Each symbol represents the air velocity. When comparison is made at constant air velocity, in estimation SMD decreases with the increase in ALR, while in the current experiment it is inverse. This is indicating the clear difference of atomization mode of prefilming atomization and pressure atomization. As for estimation, with increasing ALR at constant air velocity the liquid flow rate is decreased, which might have caused the decrease in liquid film thickness, and thus SMD is decreased. On the other hand, in the current study increasing ALR means decreasing the liquid injection pressure, and thus SMD is increased. When comparison is made at ALR lower than 10 which is the maximum ALR for the applicability of the estimation, it is clearly shown that most points of SMD obtained in this study are much less than those of conventional prefilming atomization.

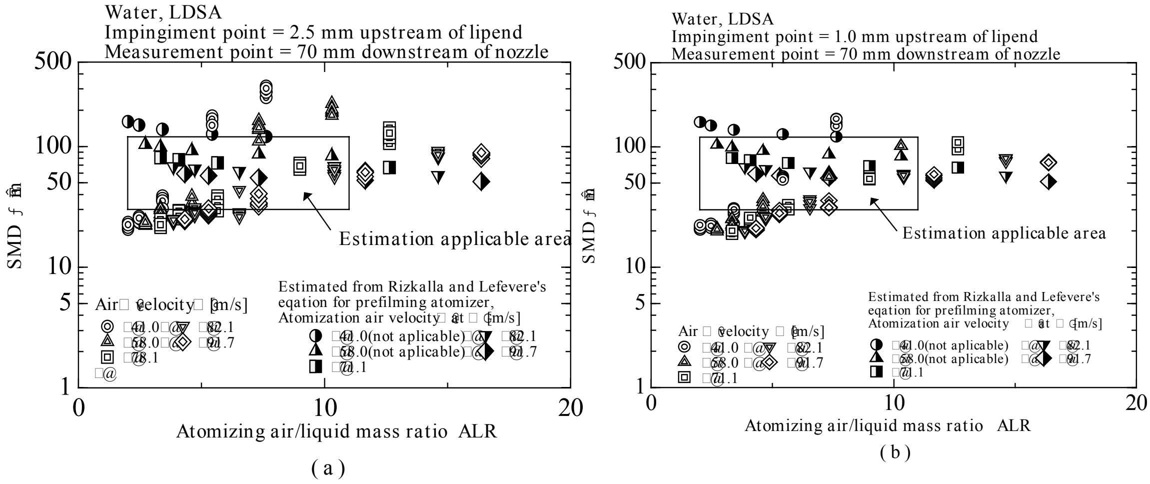


Fig.6 SMD variation with air velocity and liquid injection pressure,

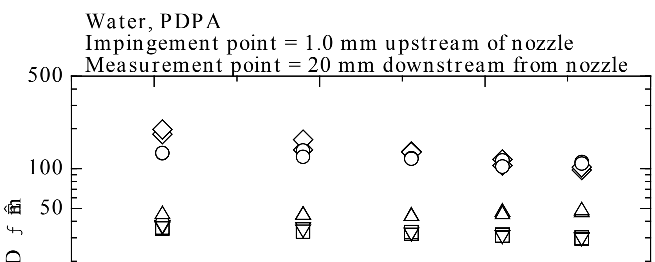
(a) Impingement point = 2.5 mm upstream of nozzle, (b) 1.0 mm.

3.3 PDPA measurement and atomization mode

In the case of LDSA measurement, the measurement position of 70 mm downstream of the burner exit was determined by the measurement optimization based on the parameter of "transmittance" evaluating the droplet concentration. However, in the case of PDPA measurement, the measurement point was set close to the burner to examine the droplet behavior just after the atomization as long as a reliability parameter of "validation" was kept acceptable level of 70 %. For this reason it was determined to be 20 mm downstream of the burner.

SMD obtained by PDPA for 1.0 mm impingement is shown in Fig. 7. The general trend of SMD dependence on the air velocity and the liquid injection pressure is almost similar to that of LDSA measurement. The absolute values of SMD for PDPA are mostly greater than that for LDSA measurement. This would be mainly due to the difference of measurement volume. LDSA measures the whole droplets along line of sight, while PDPA is almost a pin-point measurement at the central region with the highest droplet concentration, where larger droplets might be existent.

In order to suspect the atomization mode, the correlation between size and velocity of each droplet is shown in Fig. 8. It is generally accepted that droplets generated by air-blasting atomization mode exhibit negative correlation due to the fact that smaller droplets tend to fly with the air stream, while droplets generated by pressure atomization mode show positive correlation since larger liquid column has higher velocity and smaller droplets lose their momentum with progressing the atomization. In Fig. 8, when liquid injection pressure is low at 0.5 MPa, in addition to the droplets with positive correlation there appear pretty many droplets with negative correlation which would be produced by gas-blasting atomization mode. In contrast to this, at higher liquid injection pressure of 2.5 MPa where no SMD variation with air velocity was observed, almost all the droplets exhibit positive correlation. This shows that in this case almost all the droplets were produced by pressure atomization mode and air-blasting mode is little contributing. The change of atomization mode can thus be indicated by the correlation behavior of size and velocity of each droplet.



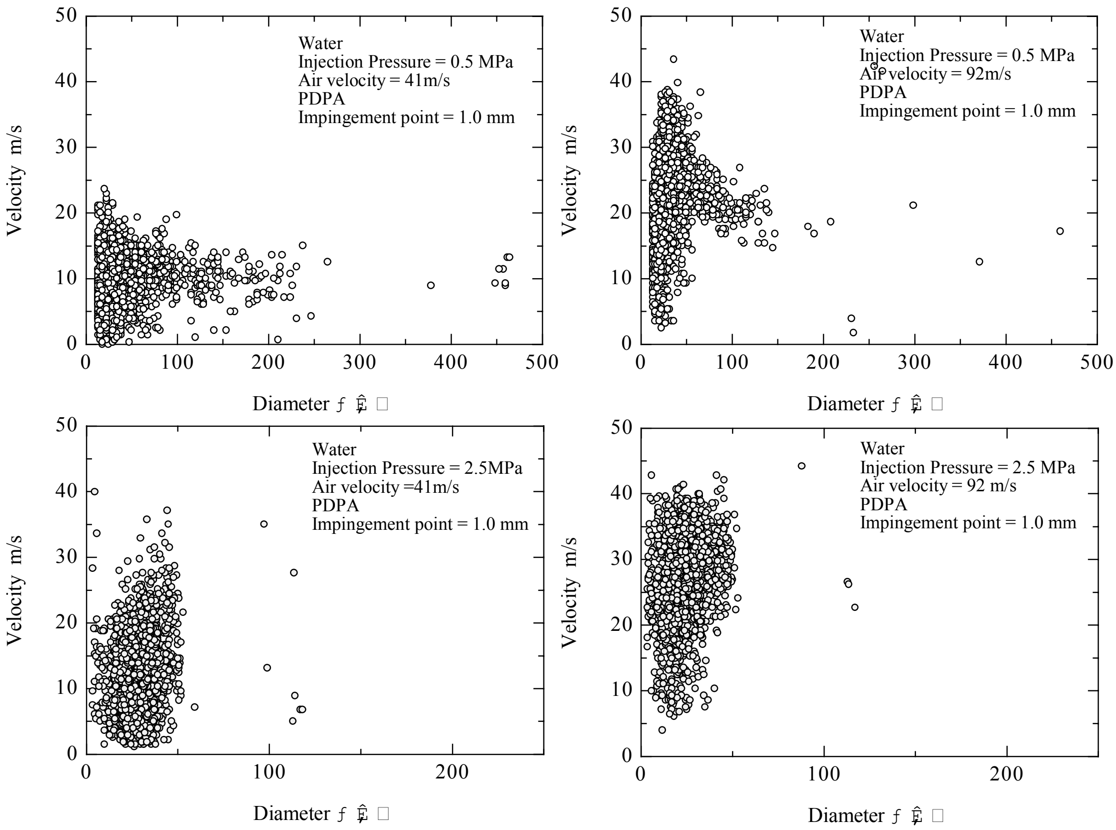


Fig.8 Effect of air velocity and liquid injection pressure on the correlation between diameter and velocity of each droplet.

4. Conclusions

(1) At lower liquid injection pressure SMD decreases with the increase in air velocity, while at higher liquid injection pressure SMD varies little with air velocity.

(2) Pressure atomization gives remarkable improvement of atomization ranging the ratio of SMD from 1/3 to 1/14.

(3) The dependence of SMD on the liquid injection pressure for this pressure atomization with wall impingement is less than that for the pressure atomization of free jet.
(4) Under the condition of lower liquid injection pressure and higher air velocity, there is pretty good agreement of SMD between the current experiment and the estimation based on Rizkalla and Lefebvre's equation.
(5) When liquid injection pressure is lower, in addition to the droplets with positive correlation between size and velocity of each droplet there appear many droplets with negative correlation which would be produced by gas-blasting mode. At higher liquid injection pressure, almost all the droplets exhibit positive correlation, which shows that pressure atomization is predominant in this case.

Acknowledgement

This study was carried out as a cooperative research between National Aerospace Laboratory of Japan and Gunma University. The authors acknowledge Mr. Jun HORIKOSHI for his help with the preparation of manuscript.

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