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Spray jet penetration and distribution of modulated liquid jets in subsonic cross-flows †

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Abstract

Modulated liquid jets injected into subsonic cross-flows are empirically studied by using a mechanical liquid jet modulation apparatus. Experimental investigations were conducted using water over a range of cross-flow velocities from 5 m/s to 143 m/s and with modulated liquid jet frequencies from 35.7 Hz to 166.2 Hz and so on. PDPA(phase Doppler particle anemometry) was employed to measure droplet diameter and velocity with various spray cross-sections from Z/d=20 to Z/d=60. The spray structure, penetration depth, SMD(Sauter mean diameter), volume flux and velocity characteristics of modulated liquid jets injected into cross-flows were examined. As oscillation of the periodic pressure that could make liquid jet moved up and down in cross-flow field, the mixing process was facilitated. This phenomenon has the advantage of mixing the spray concentration from the center area to the outer area. Also, a bulk liquid jet puff was detected in the upper field of the liquid jet surface. The modulation effect appears significant in the extent of the spray oscillation. The correlation equations for the liquid jet boundary of the upper and lower regions which related to the Strouhal number have been presented to predict the spray structure under modulation conditions. Because of the modulation frequency, an inclination of averaged SMD for the structured layer was evanescent which contributed to the promotion of the macroscopic spray mixing process. Cross-sectional characteristics of SMD had the same tendency over a range of various modulation frequencies. As the modulation frequency increased, the region of volume flux distribution also increased.

Keywords: Modulated liquid jet; Penetration depth; Strouhal number; SMD; Volume flux

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1. Introduction

The penetration, spray dispersion angle and droplet sizes related to the breakup process for liquid jets and air/fuel distributions are very important parameters in propulsion systems requiring combustion efficiency and regulation of pollutant emissions. Liquid jets injected into cross-flow streams have been used as a common strategy for air breathing combustion engines including fuel injection in the combustor of bluff body flame-holders, dilution air through combustor walls, turbine blade cooling and thrust control of rockets via small jets. Therefore, the fundamental physics of liquid jet-breakup processes, droplet transport dynamics, and spray structures must be investigated and understood. Many projects related to spray structure, penetration and droplet properties have been conducted to study liquid jets injected into cross-flows. Penetration depth is especially important for an understanding of the physics of liquid jet disintegration [1]. Pulsed liquid jets injected into cross-flows have been examined quite extensively in order to study the dynamic characteristics of liquid jets. This technique is applied to reducing combustion instability and increasing mixing efficiency that transversely pulsed jet generally induces more turbulent effect. In the case of continuous liquid injection into a cross-flow, the more the momentum ratio is increased, the more the breakup point and penetration are increased. In the cross-flow field, the main parameter of the liquid jet for the liquid jet breakup was cross-flow drag rather than modulation frequency. Although modulation frequency has a little effect on liquid jet breakup, during the injection process, penetration depth and the mixing process can be controlled by modulated frequency. Gaseous jets injected into cross-flows composed of distinct counterclockwise vortex loops emerged to the jet in the very near field. Upstream and downstream vortexes, which depend on the jet-to-cross-flow velocity ratio, are forced to merge on each side of the loop. These mechanisms also distort and cancel the downstream vortex pair loops.

Previous studies of pulsed injection with gaseous properties in cross-flow streams include penetration depth, vortex generation and mixing process [2-6], and so on. Some of these

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Table 1. Water & air properties and nozzle specifications.

Parameter	Water	Cross-flow(air)
Temperature (K)	293±2	306±5
Density (kg/m^3)	998	1.21±0.08
Surface tension (N/m)	0.0727	-
Orifice diameter (mm)	1.0	
Orifice length. (mm)	2.5	

Table 2. Experiment conditions.

Parameter	Value
Fuel flow (g/s) (water)	5.3~12.6
Injection frequency (Hz)	35.7~166.2
Cross-flow velocity (m/s)	5~143
Momentum ratio (q)	18.7~118.0
Cross flow hydraulic diameter (mm) $d_h = \frac{2(a \times b)}{a+b}$	96
$\mathrm{Re}_{cross} = \frac{\rho_a U_a d_h}{\mu_a}$	3.03~10.05 x 10^5
$We_a = \frac{\rho_a U_{cross}^2 d_o}{\sigma_l}$	28.2~316.9

studies are focused on square wave pulsation conditions and find the optimum Strouhal number of pulsed jets injected into cross-flow streams. However, a few studies have been conducted on modulated liquid jets in a cross-flow stream. More recent scaling analysis by Johari et al. [2] studied similar trends in terms of penetration and mixing which are highly dependent on vortex interactions near the jet nozzle and through the downstream. They also proposed a classification scheme for pulsed jets in cross-flow streams that explores the influences of the square wave's stroke ratio and duty cycle. Hermanson et al. [3] studied the penetration effect of a modulated operation cycle jet. They found that penetration depth of pulsed liquid jet more increased high frequency than low frequency at the same injection pressure. A fully modulated jet at the low frequency state penetrated more than the steady state jet, which is the same as for a continuous jet. Karagozian et al. [4] using a dynamic compensator or feed-forward controller studied pulsed jet conditions related to frequency f, duty cycle α, and pulse width τ. They explained that vortex shedding is related to the Strouhal number. Vortex instability is caused by Kelvin-Helmholtz instability at the nozzle exit, and this phenomenon also emerged from the mass flow rate and velocity difference at the nozzle exit. Wu et al. [5] determined that at a pulsed jet of low frequency, a pulsed jet injected into cross-flows penetrates deeper than no pulsating jet at the same mean momentum ratio. Eroglu et al. [6] investigated the effect of periodic disturbances on the structure and mixing of a transverse jet using a laser-induced fluorescence method, and confirmed the process of vortex loop generation of under steady and unsteady conditions. Under a low pulsating condition with a square wave form modulation the vortex ring penetrated deeper than the steady jet. Narayanan et al. [7] determined that the pulsation frequency for maximized jet spread and mixing is equal to or greater than that associated with the unforced transverse jet. Elshamy et al. [8] investigated the dynamic behavior of mechanically excited liquid jets injected into subsonic air cross-flow streams. Using a phase locked PIV system, they measured the instantaneous droplet velocities in the liquid jet column region. The penetration of the jet can increase by more than 40% and the optimum excitation Strouhal number is about 0.0047. Santavicca et al. [9] studied a modulated liquid jet using a Weber number in fuel transfer functions which optimize combustion efficiency and suppress combustion instability. In this study, the input function is a time varying mass flow rate and the output function is as an injected liquid jet of Mie-scattering intensity. Anderson et al. [10] studied the modulation liquid jet in an unsteady cross-flow and showed that fuel modulation greatly improves spray mixing at the appropriate phase angle. Previous studies include the characteristics of spray structures; however, there is insufficiency data on droplet characteristics in cross-flow fields. The current study focuses on modulation of the liquid jet injected into cross-flows related to the macro and microscopic characteristics which are dynamic characteristics of spray structure, penetration, SMD and volume flux. A wide range of parameters, such as injection frequency (35.7~166.2 Hz), were selected. Then a one-component PDPA system was utilized to measure the droplet properties and the results are then discussed.

2. Experimental facility and methods

Spray characteristics of a modulated liquid jet were studied by using a modulation apparatus. Water and air properties and nozzle specifications are shown in Table 1, and experimental conditions in Table 2. A single-hole nozzle was flush mounted in the bottom plates of a subsonic wind tunnel operated by a blow type system. Fig. 1 illustrates the schematic of the present experimental configuration, which consists of a blow type wind tunnel, liquid supply systems and a PDPA system. The test section is rectangular with a test section of 120 mm (width) x 80 mm (height) x 500 mm (length). To provide for visual observation and optical instrumentation, the test section was equipped with PC(clear polycarbonate). Air stream velocities ranged from 5 to 143 m/s, the pressure drop was across the orifice about 13% of the reservoir pressure, the diameter of the orifice was 1.0 mm, and the length of the orifice was 2.5 mm, and tapered by 45° to the exit diameter. The temperature of the air stream was 306±5 K, and the humidity in the test section condition was assumed to be 50%. When experiments were conducted, the force of gravity was disregarded. Test liquids were poured into a liquid tank and pressurized by an air compressor. The liquid jet was injected into cross-flow fields at a 90° injection angle. The liquid volumetric flow rate was controlled by pressure regulators and

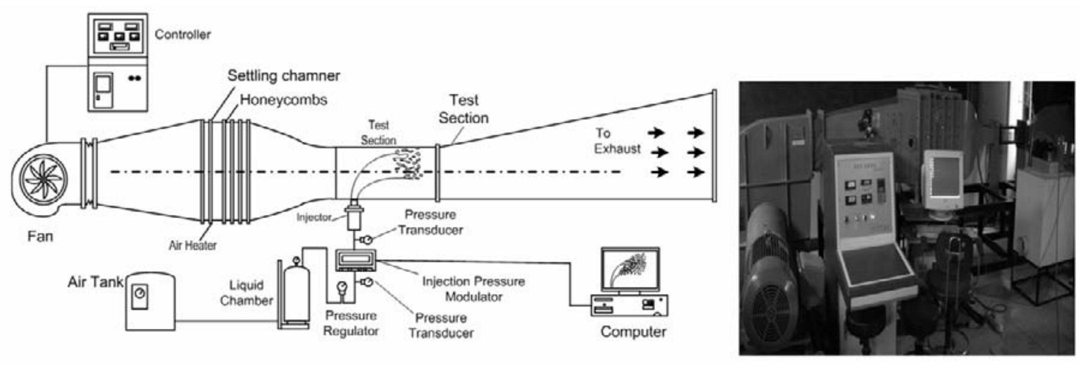


Fig. 1. Schematic of open type wind tunnel.

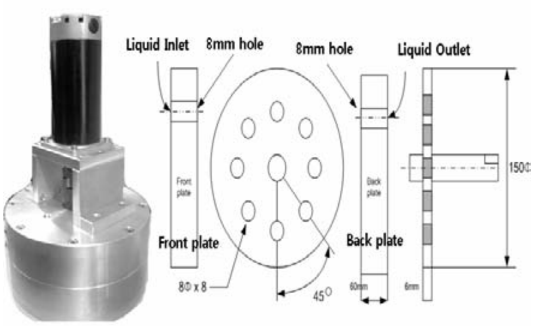


Fig. 2. Modulation apparatus and dimension.

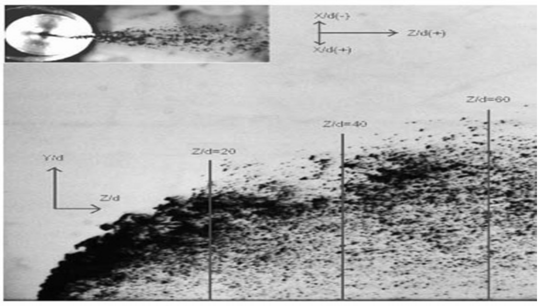


Fig. 3. Measured position for modulated liquid jet in cross-flow field.

measured by a turbine type flow meter which was calibrated to an uncertainty of less than 3%. The pressure history of the pulsed liquid jet was measured by a pressure transducer (PCB A101) in order to monitor the dynamic pressure during the injection process. Fig. 2 shows the modulation apparatus and its pressure, whose ranges varied from 35.7 to 166.2 Hz, was controlled with a mechanical pulsator by a rotating circular plate. A Phase Doppler particle analyzer was also used to determine the properties of the droplets. To measure the droplet properties, a measurement point was selected to an increment of 2.54 mm(X/d, Y/d) to the jet direction at Z/d=20, 40, 60, and its position is given in Fig. 2. Regions with unbroken liquid core, regular ligaments, and non spherical droplets, where PDPA measurement cannot be carried out reliably were avoided for the determination of detailed structures of the entire cross-section. Phase Doppler particle anemometry (PDPA) was used to obtain quantitative data about the distribution properties of the spray. Data was taken at many points at each location at the x/d, y/d and z/d axis, depicted in Fig. 3. Droplet velocities were measured in the vertical direction of the spray plume. For the penetration depth measurement, the edge of the spray plume was probed even though the entire spray structure was not suitable for detailed PDPA measurement. Droplet properties at spray plume areas with high density were averaged over more than 20,000 droplets at each point of non-dimensional location in order to reduce experimental uncertainties.

Measurement data was neglected when the measured liquid volume flux was below 0.01 $cm^3/s/cm^2$. Images of the pulsed liquid jet captured by a CCD camera were stored inside a computer by using a frame grabber. Analysis of spray images used for macroscopic phenomena of penetration depth and dynamic structure of spray were averaged for each test condition in order to reduce any experimental uncertainty due to the unsteadiness of the spray structure.

3. Results and discussion

3.1 Spray structure and penetration

Measurements were taken of a liquid jet injected without cross-flow conditions to verify the continuous and modulated spray structure. Fig. 4 depicts the pure liquid jet injected into non-cross flow fields and the modulated liquid jet without cross flow. For the vertical injection of a continuous liquid jet, the surface of the liquid column shows a smoothing phenomenon; however, the modulated liquid jet shows an unsteady phenomenon: pressure pulsation helps to regularize the instability of the liquid column. The momentum ratio (q) is 35.55(100 kPa) and the frequency of the modulated liquid jet is 35.7 Hz. By comparing these two images, a bulk of liquid jet puff was detected at the upper field of the modulated liquid jet surface.

This phenomenon has the advantage of mixing the spray and keeping it from being concentrated in the bottom region, but, instead sprays to the outer region. The liquid puff generated randomly at the liquid upper surface is the main parame-

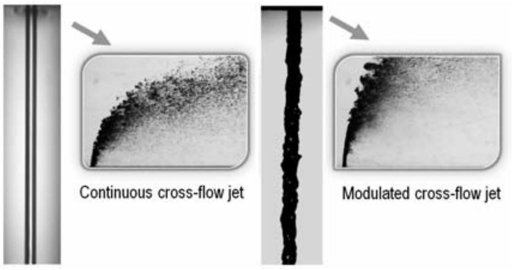


Fig. 4. Spray images of continuous liquid jet and modulated liquid jet.

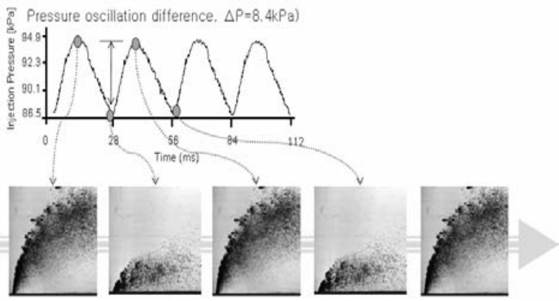


Fig. 5. Oscillation process of modulated liquid jet at 35.7 Hz.

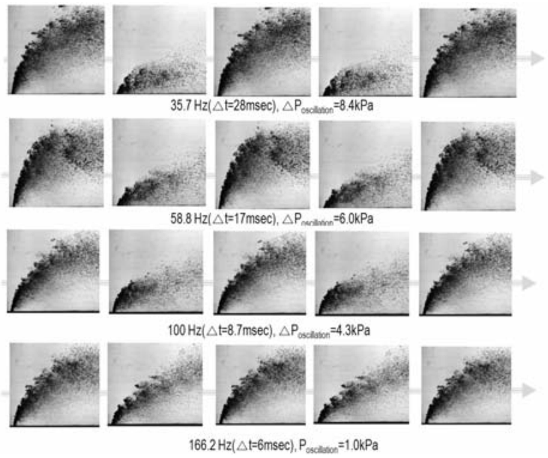


Fig. 6. Liquid jets images with various modulation frequency.

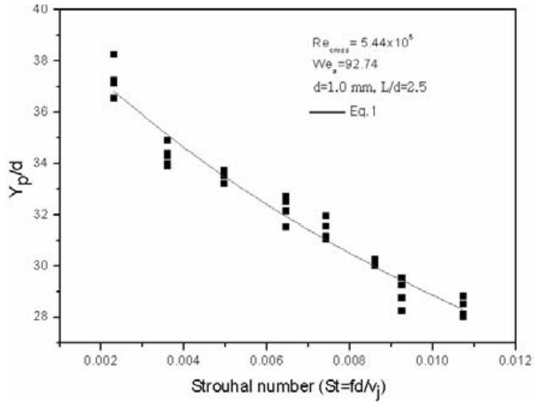


Fig. 7. Spray penetration with various Strouhal numbers.

ter affecting mixing of the spray field. Typically, when a jet with a square wave form was injected into cross-flows, penetration of the gaseous jet increased and separated into two branches [4]; however, in the case of a liquid jet injected into cross-flows with a higher injection frequency, the higher injection frequency caused decreasing penetration depth [8]. Fig. 5 demonstrates spray images of the modulated liquid jet injected into cross-flows with an injection frequency of 35.7 Hz and momentum ratio of 35.55. At 35.7 Hz, a pressure of 94.9 kPa and 86.5 kPa periodically oscillated. Pressure periodically oscillated in the bottom of the injector and one cycle of injection period is 28 msec with a sine-wave form.

Liquid jets at maximum pressure penetrated the upper region in the cross-flow field, and penetrated the bottom region at minimum pressure. Fig. 6 depicts spray images of the liquid jet injected into cross-flows for a modulated liquid jet. The difference of mass flow rate from 0 Hz to 166.2 Hz was only 0.7 g/s. (mass flow of 0 Hz is 11.9 g/s and 166.2 Hz is 12.6 g/s.) At 35.7 Hz, the trajectory oscillation is moved to the Y axis about Y/d=25 (25 mm) at 35.7 Hz and Y/d=8 (8 mm) at 166.2 Hz. As modulation frequency increased, penetration depth decreased. This is because the rotating plate causes a decrease in total pressure. But, as the modulation frequency was increased from 35.7 Hz with Δ p=8.4 kPa to 166.2 Hz with Δ p=1.0 kPa, spray structures resemble the injection processes of a continuous liquid jet. The penetration depth is defined by the liquid jet location at Z/d=20. Fig. 7 shows the spray penetration with various Strouhal numbers which can be used to study non-dimensional fluid vibration mechanisms. As the Strouhal number increases, the penetration depth decreases and spray structures approach those of the continuous liquid jet. This is because the pressure differences between maximum and minimum pressure decreased from 8.4 kPa to 1.0 kPa. Using the shadow-graph method, experimental correlations for the penetration depth were developed. The developed correlation equation is well fitted with the whole penetration point and is presented in Eq. (1). In this equation, average deviation was 0.251, and the coefficient of determination, R^2=96.3%.

$$\frac{Y_P}{d} = q^{0.67} We_a^{-0.07} \exp^{\left(\frac{0.057}{St+0.036}\right)} \tag{1}$$

The averaged trajectory line of the outer boundary with maximum pressure and minimum pressure are shown in Fig. 8 and Fig. 9. The modulated liquid jet has a different pressure perturbation, which influences penetration, mixing process, and combustion instability suppression. The correlations and the transverse coordinates of the data have been scaled by $f^{0.9283}$, $q^{0.011}$ and $We_a^{-0.7544}$ to make them independent of frequency, momentum ratio and Weber number. Average deviation of Eq. (2) was 0.273, and the coefficient of determination, R^2=94.1%. Eq. (3) has the average deviation of 0.281, and the coefficient of determination, R^2=92.4%.

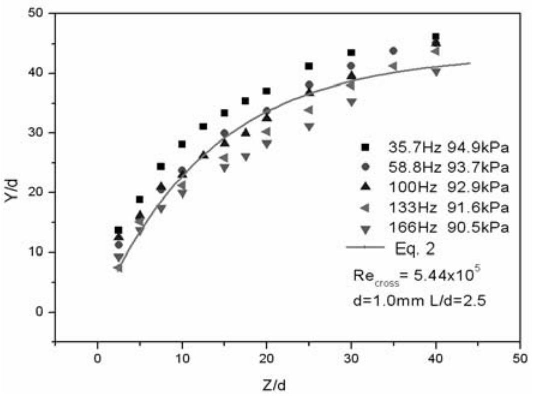


Fig. 8. Spray outer boundary at maximum pressure states of trajectory in cross-flow with various modulation frequencies.

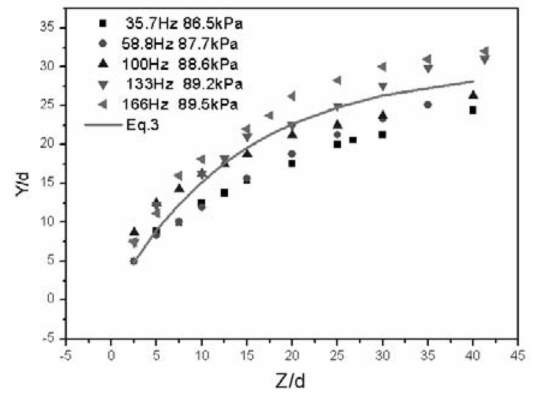


Fig. 9. Spray outer boundary at minimum pressure states of trajectory in cross-flow with various modulation frequencies.

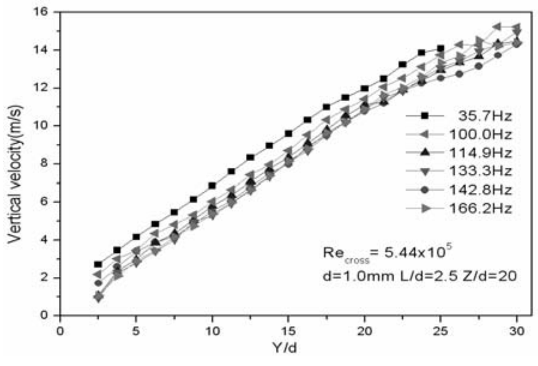


Fig. 10. Comparison of vertical velocity with various modulation frequencies (X/d = 0, Y/d=0~30).

$$\frac{Y}{d} = 45.13\times(1-\exp^{-0.075(\frac{Z}{d})})\times(1-f^{-0.9283})\times q^{0.011}\times(1-We_a^{-0.7544}) \tag{2}$$

$$\frac{Y}{d} = 30.25\times(1-\exp^{-0.071(\frac{Z}{d})})\times(1-f^{-0.9283})\times q^{0.011}\times(1-We_a^{-0.7544}) \tag{3}$$

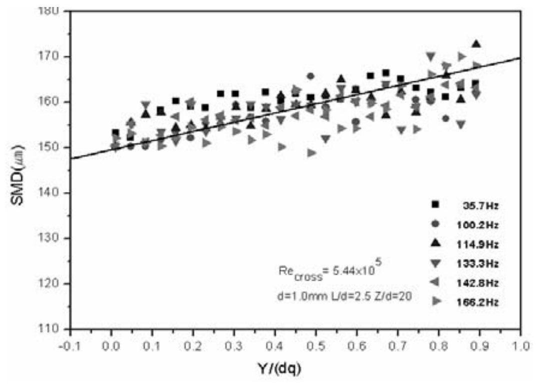


Fig. 11. Comparison of SMD values with various modulation frequencies (X/d = 0, Y/d=0~30).

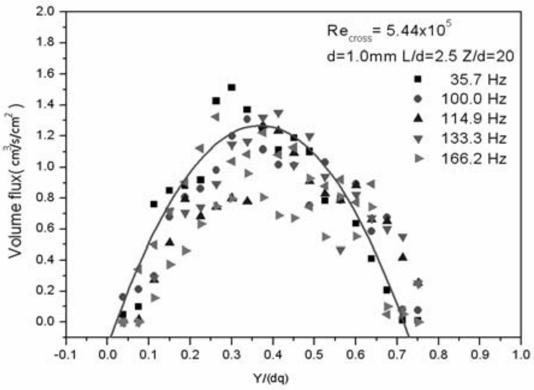
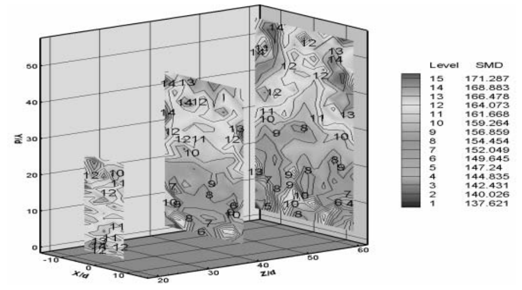
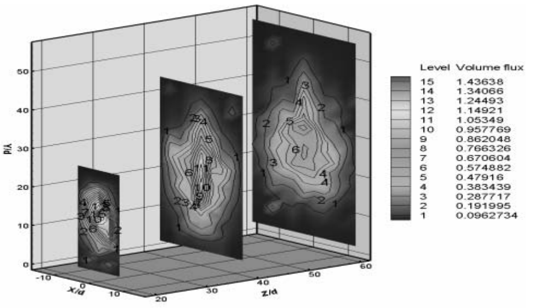


Fig. 12. Comparison of volume flux values with various modulation frequencies (X/d = 0, Y/d=0~30).

Also, to verify the effect of modulation, the vertical velocity of the spray jet was analyzed by PDPA through the spray plume of the center axis. Measured vertical velocities with various modulation frequencies are plotted in Fig. 10. The spray jets injected into cross-flows are bent by the cross-flow drag force which is related to the momentum ratio. In all test cases, a low modulation frequency shows a higher velocity profile than the high modulation frequency due to the high momentum ratio and high penetration depth. Fig. 11 illustrates SMD values at 35.7 Hz ~ 166.2 Hz. Measured positions are directly scanned through Y/d=0 to Y/d=30 at X/d=0. In these cases, experimental results indicate that SMD are distributed from 148 to 173 μm . In case of continuous spray injected into cross-flows, maximum value of the SMD emerged from the top of the spray plume and minimum value of the SMD emerged from the spray bottom region. Larger droplets with higher momentum energy in the jet injection direction can travel farther to the outer boundary of the spray plume, while small droplets with lower momentum are distributed in the bottom of the spray plume. SMD values through the spray center axis are randomly distributed with various modulation frequencies. This is because of the oscillation phenomenon of spray the jet, which was measured from point to point. This large-scale droplet oscillation motion greatly promotes non-uniform distribution in the spray plume, therefore, significantly enhancing mixing between spray and air.

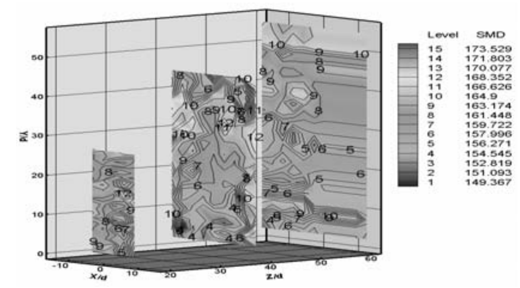


(a) SMD

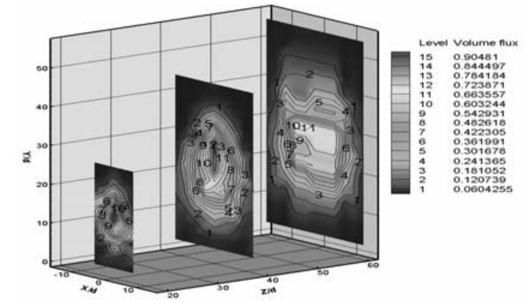


(b) Volume flux

Fig. 13. Cross-sectional contour of (a) SMD, (b) volume flux at St=0.0023 (P_i=100 kPa, d=1.0 mm, L/d=2.5).



(a) SMD



(b) Volume flux

Fig. 14. Cross-sectional total contour of (a) SMD, (b)volume flux 3D multi-view in cross-flow at St=0.0107 (P_i=100 kPa, d=1.0 mm, L/d=2.5).

The difference of the mass flow rate influences the spray density and volume flux, so a modulated liquid jet under cross-flow conditions can be used as an effective technique to achieve compensation of a good mixing leading and breakup process. Fig. 12 shows the volume flux distribution with various modulation frequencies. The modulation effect that was induced by the simultaneous pressure perturbation of the liquid jet injected into cross-flows led to a decrease in volume in the volume flux ratio.

3.2 Spray distributions

The cross-sectional contour of the SMD and the volume flux were used for each Strouhal number which is a non-dimensional parameter of frequency characteristics related to orifice diameter and injection velocity of liquid jet. The values of Strouhal number 0.0023 and 0.0107 are illustrated in Fig. 13 and Fig. 14. For the modulated liquid jet, whose pressure oscillation was induced by a rotating disk, the SMD for the structured layer was evanescent compared to the continuous cross-flow spray jet. Cross-sectional characteristics of the SMD at the whole area showed a non-structured distribution due to the oscillation of the pulsed liquid jet in the cross-flow stream. The effect of the oscillation motion can increase the mixing of the liquid jet injected into cross-flows. The characteristics of the volume flux continuously decreased from the center region to the edge of the plume. Volume flux contours for St=0.0023 and St=0.0107 were very similar. And overall mass flows rates are the same for St=0.0023 and St=0.0107. The effect of an increase in modulation frequencies is a marked decrease in the maximum volume flux value from 1.43 $cm^3/s/cm^2$ to 0.90 $cm^3/s/cm^2$. The volume flux exhibits a maximum value in the spray core and decreases from the center region to the edge of the plume. For St=0.0107, the spray plume areas are wider than St=0.0023.

4. Summary

The characteristics of a modulated liquid jet injected into cross-flows with various frequencies have been studied experimentally. As the pressure oscillation experiences periodical perturbation, the modulated liquid jet experiences an unsteady motion into cross-flows. Also, a bulk of liquid jet puff was detected in the upper field of the liquid surface which was caused by a droplet catch up process. It is possible to speculate that this phenomenon can provide a distinct advantage by improving the mixing process. As the Strouhal number, which was related to modulation frequency, increased, the penetration depth decreased. And penetration has been correlated with modulation frequency, Weber number and non-dimensional stream-wise distance Z/d. SMD values were seen to be a non-structured distribution in the spray plume at 35.7 Hz to 166.2 Hz. Further, volume flux shows a maximum value in the spray core and decreases from the center region to the edge of the plume. The effect of an increase in modulation frequencies is a marked decrease in maximum volume flux value.

Acknowledgment

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Nomenclature

d : Nozzle diameter
d_h : Hydraulic diameter
f : Injection frequency
L : Orifice length
P_i : Liquid injection pressure
q : Momentum ratio, $(\rho_L v_j^2 / \rho_G v_G^2)$
Re_{cross} : Reynolds number of cross-flow
St : Strouhal number, (fd/V_j)
SMD : Sauter Mean Diameter
V_i : Liquid injection velocity
We_a : Weber number of cross-flow
Y_p : Penetration depth
Y/d : Non-dimension number of spray height
Z/d : Non-dimension number of spray length

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