Effects of Momentum Rate on the Mixing of the Spray of Doublet Impinging Jets

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Abstract

In this research, Planar Laser Induced Fluorescence (PLIF) technique was adopted to determine the mass probability distribution of droplets to observe the mixing phenomena in the sprays of the like-doublet, equal-momentum impinging jets at various jet momentum rates (900 g · cm/s² < \( \dot{m} \nu < 38000 \text{ g · cm/s}^2 \)). The injector was composed of two 0.3mm orifices (L/d =5) oriented to have a +30°/-30° impinging angle. Water (\( \sigma \sim 71.8 \text{ N/m} \)) and acetone(10vol%) in water solution (\( \sigma \sim 51.2 \text{ N/m} \)) were adopted as the test liquids. In order to describe the mixing phenomena, the penetration percentage (\( \cdot PP \)) of droplets from either jet was identified from PLIF observations. For the present research, the best mixing occurred at the \( \cdot PP \) close to 50%. Coupled with Malvern measurements, the mean droplet sizes (\( d_{50} \)), the mean Webber number (\( \overline{We}_e \)) based on droplet lateral motion, and the collision probability among droplets in the sprays were estimated to interpret the distribution of the observed \( \cdot PP \) at various momentum rates. The mixing of the sprays was identified into two distinct types: film-mixing control in the open-rim sprays, and droplet-penetration control in the fully-developed sprays. The convective interaction (turbulence) within the merging zone of the open-rim impinging sprays may responsible for \( \cdot PP \) observed in the low momentum rates. In the fully-developed conditions, experimental observations showed an increasing of \( \cdot PP \) from 54% to a maximum of 61% at lower momentum rates (4000 g · cm/s² ~7500 g · cm/s²) for water impingements was due to the sharp decreasing of the collision probability with increasing momentum rates. At the momentum rates between 7500 g · cm/s² and 14000 g · cm/s², \( \cdot PP \) decreased to 51% mainly caused by the increasing \( \overline{We}_e \) (>13) that turned the outcome of droplet collision preferring reflexive separation and prohibited droplets to penetrate. At higher momentum rates (>14000 g · cm/s²), the increasing \( \overline{We}_e \) (>25), increased the probability of stretching separation from droplet collisions, thus induced a gradual increase of \( \cdot PP \) with momentum rates. Similar results for the impingements of acetone-water solution were also observed. However, the values of \( \cdot PP \) for acetone-water sprays were always greater than that of water sprays due to the effects of lower collision probability and higher \( \overline{We}_e \).

Introduction

In the liquid rocket propulsion system, the technique of liquid-liquid impingement is commonly used in the injector design because of its simultaneously atomizing and mixing effects of the liquid propellants. Although the configuration of the jet impingement is simple, the impinging spray is intricately affected by jet’s velocity, momentum rate, physical property of liquids, and the arrangement of the orifices. Those parameters determine the mass and mixture ratio distributions of the propellants which significantly affect the thermal and combustion characteristics of the rocket engines.

Conventionally, the mass distribution of sprays were analyzed by mechanical patternator.[1, 2] Deduced from doublet impinging jets experiments, Ashgriz et al.[2] inferred that the mixing of the sprays would be determined by the reflective and transmissive (mutual penetration) motions of the atomized liquid, which are characterized by jet’s velocity. Rupe [1, 3] investigated the mixing of doublet impinging water jets with various orifice configurations. Besides defining the mixing efficiency, Rupe found that the momentum rate ratio and the diameter of the orifices must be equal to acquire the optimum spray uniformity and mixing. Similar results were also demonstrated by Won. et al.[4] in his studies of unlike doublet and split triplet impinging sprays.

The breakup of doublet impinging jets was differentiated into patterns by jet velocities.[5, 6] At a high enough jet velocity, spray appears to be fully developed that the liquid jets break up and atomize immediately after impingement. Since the breakup and atomization of liquid jets are considered to be caused by jet’s aero-
dynamic and hydrodynamic instabilities [7, 8], viscosity of the liquid which affects the jet’s hydrodynamic instability is one of the crucial elements determining the starting velocity of fully-developed spray pattern. However, at fully-developed velocities, surface tension of the liquid which affects the aerodynamic instability is much more influential than viscosity on liquid atomization.[9]

In the investigation of droplet size distribution of impinging sprays, the SMD of droplets were observed to decrease with increasing jet velocity.[6] A phase Doppler particle analyzer (PDPA) was adopted to examine the doublet impinging water jets with various mass flow rates, the results showed that liquid flow rate crucially control the atomization of the impinging jets and a critical mass flow rate produced an optimum atomization of the liquid jets.[10]

For the fully-developed sprays, lateral motion of the droplets below the impinging point may occur and causes secondary collision and further liquid mixing. Especially in the dense spray system, the effect of droplet collision significantly alters the spray characteristics.[11] From the experimental observations, the outcome of binary droplet-droplet collision was described by bouncing, coalescence, separation (reflective & stretching), and shattering from the differences of Weber number (We) and impact parameter (b), etc.[12] For small values of Weber number and impact parameter, droplet coalescence was favored. However, for large We and b, the collision resulted in either bouncing or temporary coalescence and eventual separation with or without additional satellite droplet.[13] The outcome of binary collision between droplets was characterized into different regimes by b and We.[14]

As was shown that the momentum rate of liquid jets significantly affected the impinging spray phenomena [1-3, 10], this research investigated the mixing phenomena of impinging jets. The mass distribution of the spray from individual impinging jets was detailed analyzed by Planar Laser Induced Fluorescence (PLIF) technique.[15-16] Together with the information of the droplet size, the complex mechanism of the mixing of impinging jets was comprehended in depth.

Experimental Apparatus and Techniques

In this study, a nitrogen-compressing flow control system was used to accurately supply the liquid flow to the doublet impinging jet experiments (see Fig.1). The injector was composed of two orifices of ϕ 0.3 mm (L/d =5) oriented to have a +30°/-30° impinging angle. With different surface tensions, water (σ=71.8 N/m) and acetone(10vol%)-water solution (σ=51.2 N/m) were adopted as the test liquids. The physical properties of the test liquids are listed in Table 1. For the experiments, the momentum rate ratio of the impinging jets was kept unity, and the momentum rates were varied from 900 g·cm/s² to 38000 g·cm/s².

The front-view and side-view snap-shot images of the sprays of doublet impinging jets were taken to acquire the spray angle variations at different jet momentum rates. The scatter-light intensity probability distribution of the images at 15mm downstream of the impinging point were fitted by Gaussian function (see Fig. 2), and, 85% of the total light intensity was used to defined the width of the spray fan (w). Coupled with the distance (d) from impinging point and the impinging angle (θ), the spray angles were calculated by

$$\theta = 2\tan^{-1}\left(\frac{w/2}{d}\right)$$

(1)

PLIF technique was adopted to observe the 2-D droplet mass distributions (see Fig. 3). The 1mm×50mm laser sheet (532nm) from a second-harmonic Nd-YAG laser (Model LOTIS TII) was aligned to cross the spray fan to excite the droplets containing laser dye (Sulforhodamine 101). A 600nm high-pass filter was used to attenuate the scattered laser light and the fluorescent images of the sprays were acquired with a pseudo-color synchronous CCD camera (1600×1200 pixels). The shutter speed of the camera was 110 μsec and the resolution of the image was 0.05mm. In each experiment, average of 100 fluorescent images was recorded for statistical analysis. Since the local fluorescent intensity of the images is linearly proportional to the local liquid mass [15-16], 2-D droplet mass density probability distributions was able to be constructed from the fluorescent images. As is shown in the right of Fig. 3, the constant probability contours of 2-D droplet mass distribution was thus identified.

The spray patternation index (P.I.) [17] and the mixing efficiency (E_m) [1] were also evaluated in this study. Patternation index (0~200) represents the uniformity of the spray distribution where zero of the P.I. is the most uniform state. E_m of 100% indicates the perfect mixing between two liquids. In addition, penetration percentage (P.P.) was also used to indicate the mass percentage of the spray from one impinged jet to cross the center line and penetrate to the other side as shown in Fig. 4.[18] For like-doublet jets impinging sprays with the same orifice size and flow momentum rate, P.P. of 50% would ideally result in the optimum mixing efficiency of 100%.

Besides PLIF measurement, the mean droplet sizes (d_{32}) distribution of the spray were measured by a Malvern Spraytec particle size analyzer. By incorporating d_{32} distribution data with the mass probability dis-
Experimental Results

The 2-D droplet mass distributions of fully-developed water impingements at different downstream positions were firstly identified in this study. The penetration percentage \( (P_P) \) and mixing efficiency \( (E_m) \) deduced from the mass distribution data are plotted in Fig. 5. The increasing \( P_P \) and decreasing \( E_m \) with the downstream distance indicated that the atomized droplets preceded lateral motion to cause the phenomenon of mutual penetration of the droplets from the two different jets. In the spray cone, the mixing condition is not conserved and may crucially depend on the fundamental droplet-droplet interactions which would closely relate to the initial momentum possess by the liquid jets.

Total of 66 impinging experiments \((900 \, \text{g} \cdot \text{cm}^2/s^2 \sim 38000 \, \text{g} \cdot \text{cm}^2/s^2)\) were performed to detailed study the relations between mixing phenomena and jet’s momentum rates. The experimental conditions and results of 30 experiments are listed in Table 2 and 3. \( P_P \) and \( E_m \) listed in the table were at 15mm downstream distance from the impinging point. In the observations, the fully-developed sprays for water impingements appeared beyond \( \sim 4000 \, \text{g} \cdot \text{cm}^2/s^2 \), while the fully-developed condition for acetone-water solution impingements appeared beyond \( \sim 2300 \, \text{g} \cdot \text{cm}^2/s^2 \).

Figs. 6 and 7 show the variation of \( P_P \) with momentum rate of water impingements and acetone-water solution impingements, respectively. Obvious changes (turning) of \( P_P \) at the starting of fully-developed spray condition were observed for both test solutions. In conjunction with the snap-shot image observations (see Fig. 8), the mixing mechanism of the spray was identified by two distinct types: film mixing control in the open-rim spray condition, and droplet-penetration control in the fully-developed spray condition.

For film mixing at low momentum rate conditions, the convective interaction (turbulence mixing) within the liquid jet merging zone shall control the jets mixing. Since the increase of the jet momentum rate increases the turbulent intensity and, however shorten the length of merging zone and mixing time as well, \( P_P \) and \( E_m \) variations in the film mixing condition shall dynamically controlled by the occurrence of turbulence and are not the focus of this research.

In the droplet-penetration control in fully-developed sprays of water, experimental results shown in Fig. 6 illustrates that \( P_P \) variations can be distinguished into three stages: a sharp increasing of \( P_P \) from 54% to a maximum of 61% in the first stage \((4000 \, \text{g} \cdot \text{cm}^2/s^2 < \dot{m}u < 7500 \, \text{g} \cdot \text{cm}^2/s^2)\), followed by a sharp decrease of \( P_P \) to 51% in the second stage \((7500 \, \text{g} \cdot \text{cm}^2/s^2 < \dot{m}u < 14000 \, \text{g} \cdot \text{cm}^2/s^2)\), and a gradual increase of the \( P_P \) in the third stage \( (\dot{m}u > 14000 \, \text{g} \cdot \text{cm}^2/s^2) \). Similar variations of \( P_P \) with momentum rate (Fig. 7) were also observed for the acetone-water solution whose surface tension \((51.2 \, \text{N/m})\) is 28.7% lower than water \((71.8 \, \text{N/m})\). For both test solutions, the best mixing of the fully-developed impinging sprays occurred at \( P_P \) closer to 50% corresponding to the momentum rate at the end of the above defined second stages.

Front- and side-view spray angles at the 15mm downstream of the impinging point were determined from the snap-shot images for water impingement experiments. As is shown in Fig. 9, the side-view spray angles caused by the mutual compression of the impinging liquids were always larger than the front-view angles at various momentum rates. In the fully-developed conditions, the front-view angles kept nearly constant (\( \sim 30^\circ \)) while the side-view angles increased with momentum rates in the first stage of droplet penetration mixing. Beyond the first stage, the side-view angles kept nearly constant at \( \sim 90^\circ \). These observations showed the shape and the spatial volume of the spray cone were almost invariant at second- and third-stage conditions of high momentum rates.

Analysis and Discussion

Based on the assumption that droplet’s lateral motion controls the degree of droplet’s mutual penetration percentage as well as the mixing efficiency of fully-developed impinging sprays, the Webber number and collision probability of droplets lateral motion would be the important factors to be estimated in order to comprehend their mixing mechanism.

By Malvern Spraytec particle size analyzer, the \( d_{32} \) (SMD) distributions of the droplets were identified at different momentum rates. In conjunction with the mass probability distribution information from PLIF observations, the averaged \( d_{32} \) of all the droplets in the cross section plane located at 15mm downstream from the impinging point were estimated and are plotted in Fig. 10. The results showed that the averaged \( d_{32} \) \((\bar{d}_{32})\) for both water and acetone-water test liquids decreased sharply with increasing momentum rate close to their fully-developed points. At higher momentum rates, the effect of momentum rate on \( \bar{d}_{32} \) diminished gradually. It was interesting to see that \( \bar{d}_{32} \) of the lower surface tension test solution (acetone-water) was smaller than that of water before their momentum rate reached
\( \sim 7000 \, g \cdot cm/s^2 \). At high momentum rates, \( \overline{d}_{32} \) of either test liquid approached a limiting size.

The mean relative lateral velocity is also estimated in order to calculate the Webber number of droplets. Since the observation position was close to the impinging point, the aerodynamic effect on droplets was assumed negligible, that is, the break up and atomization of the liquid jets consumed only the lateral (horizontal) momentum and lead the vertical velocity component of droplets unchanged. Thus, the lateral velocity (\( v_x \)) can be determined by

\[
 v_x = \left( v_{jet} \cos \theta \right) x \overline{d}
\]  

where \( v_{jet} \) is the jet velocity, \( \theta \) is the impinging angle (60°), \( x \) is lateral distance to the impinging center line, and \( \overline{d} \) is the downstream distance from impinging point. The weighted mean lateral velocity of the spray (\( \overline{v}_x \)) was estimated by

\[
 \overline{v}_x = \sum P_{mx} v_x
\]  

where \( P_{mx} \) is the probability of mass distributed at the lateral position \( x \), which was determined by the PLIF experimental results. The calculated \( \overline{v}_x \) for both test solutions at different momentum rates are plotted in Fig. 11. The results showed that \( \overline{v}_x \) increased with increasing momentum rates in the range of study, and the mean lateral Webber number of the droplets (\( \overline{W}_{e_x} \)) considering only the lateral motion of the droplets in the spray was then calculated by

\[
 \overline{W}_{e_x} = \frac{\rho \overline{v}_x^2 \overline{d}_{32}}{\sigma}
\]  

where \( \rho \) and \( \sigma \) are the density and the surface tension of the test solution, respectively. The results of the calculated \( \overline{W}_{e_x} \) are shown in Fig. 12, which indicates \( \overline{W}_{e_x} \) increased almost linearly with increasing momentum rates.

Since droplet collisions obviously affect \( P.P. \), the probability of droplet collision at the different momentum rates are required to be estimated. Consider a thin slice (1mm thick) of the spray fan located at 15mm downstream of the impinging point as the control volume, and defining \( M_p \) as the liquid mass of one (left) jet moving toward the other side (right) with droplet collision, then

\[
 M_p \propto (Z\Delta t) \cdot \overline{m}_d
\]  

where \( Z \) is the droplet collision rate, \( \Delta t \) is the time for spray to travel through the control volume (\( V \)), and \( \overline{m}_d \) is the averaged droplet mass (\( \overline{m}_d \)). The total collision number can be expressed as

\[
 Z\Delta t = \overline{m}_{32} n \overline{v}_x \Delta t
\]  

where \( n \) is the number density of the droplets in the control volume. So, equation (5) becomes

\[
 M_p \propto \frac{\overline{m}_{32}}{V} \frac{N_i}{V} \overline{v}_x \Delta t \cdot \frac{n \overline{m}_d}{V} \overline{v}_x \Delta t (M_d)
\]  

Dividing both side by the total droplet mass \( M_d \), the collision probability \( P \) was correlated to the variables by

\[
 P \propto \frac{M_p}{M_d} \propto \frac{n \overline{m}_d}{V} \overline{v}_x \Delta t \propto \frac{n \overline{m}_{32}}{V} \overline{v}_x \Delta t
\]  

The distribution areas of droplets (\( A_i \)) at 15mm downstream were estimated from the mass probability distributions from PLIF observations. For different momentum rates, the observed \( A_i \) are shown in Fig. 13. The \( \overline{d}_{32} \) and \( \overline{v}_x \) in equation (8) were previously defined. Since \( \Delta t \) is a fixed value of 1mm, with the same previous assumption that the vertical velocity of droplets is the same as the exit vertical velocity of liquid jets, \( \Delta t \) can be easily obtained for different momentum rate experiments.

The calculated dimensionless term \( \left[ \frac{n \overline{m}_{32}}{V} \overline{v}_x \Delta t / A_i \Delta d \right] \) at various momentum rates were proportional to the collision probability (\( P \)) of droplets and are plotted in Fig. 14. The results showed that the values of this dimensionless term for water impingements sharply decreased as the momentum rate increasing to 15000 g · cm/s² and then almost invariant.

With the analysis results of droplet’s Webber numbers and collision probabilities in sprays, the variation of \( P.P. \) with momentum rate shown in Fig. 6 for water impingements can be interpreted as follows:

In the 1st stage (4000 g · cm/s² < \( \overline{m}_v \) < 7500 g · cm/s²) of fully-developed conditions, the values of \( \left[ \frac{n \overline{m}_{32}}{V} \overline{v}_x \Delta t / A_i \Delta d \right] \) for both water impingements sharply decreased with increasing momentum rates, that is, higher probabilities of droplets would
move forward laterally without the interruption by collision with other droplets. This was the major reason that \( P.P. \) increased with increasing momentum rates in this stage.

In the 2nd stage \((7500 \text{ g} \cdot \text{cm}^2/\text{s}^2 < \dot{m} \nu < 14000 \text{ g} \cdot \text{cm}^2/\text{s}^2)\), although the values of \( [\pi d_s^3 ] \frac{\Delta t}{A_s \Delta d} \) still decreasing, the calculated \( \overline{W_e} \) increased to above 13. This may altered the result of droplet collision from mostly coalescence at lower \( \overline{W_e} \) in the first stage to partly reflexive separation in the second stage[12,14]. Since reflexive separation of the collision droplets inverted the direction of droplet’s motion that would greatly reduce the amount of penetrated droplets caused the decrease of \( P.P. \) with increasing momentum rate in the second stage.

In the 3rd stage \((\dot{m} \nu > 14000 \text{ g} \cdot \text{cm}^2/\text{s}^2)\) with higher \( \overline{W_e} \) (>25), the enhance off-centre separation or stretching separation from droplet collisions greatly reduced the ability of reducing \( P.P. \) by droplet collision. Although the values of \( [\pi d_s^3 ] \frac{\Delta t}{A_s \Delta d} \) kept almost constant in this high \( \overline{W_e} \) stage, the increasing ineffectiveness of collision to stop droplet penetration with momentum rate induced the slow rise of \( P.P. \) with momentum rate.

Compare to water sprays, the fully-developed conditions of acetone-water test liquid were achieved at lower jet momentum rates due to lower surface tension. As shown in Fig. 14, the values of \( [\pi d_s^3 ] \frac{\Delta t}{A_s \Delta d} \) for acetone-water sprays decreased faster and were less than that of water sprays before the momentum rates of \( \sim 10000 \text{ g} \cdot \text{cm}^2/\text{s}^2 \). This explains the higher \( P.P. \) for acetone-water sprays than that of water sprays in the first stage of fully-developed conditions shown in Fig. 6 and 7. At the momentum rate above \( \sim 10000 \text{ g} \cdot \text{cm}^2/\text{s}^2 \), the acetone-water sprays were with higher values of \( [\pi d_s^3 ] \frac{\Delta t}{A_s \Delta d} \) than that of water sprays, however, with larger values of \( \overline{W_e} \) that induced the outcomes of droplet collisions more favor to stretching in or reflexive separations, the acetone-water sprays exhibited higher values of \( P.P. \) in the second and third stages of fully-developed conditions as shown in Fig. 6 and 7.

**Conclusion**

Taking the high-resolution advantage of PLIF technique, the detail changes of penetration percentage \( (P.P.) \) at 15 mm downstream from impinging point in the sprays of the like-doublet impinging jets were observed at various momentum rates. Couple with the droplet size data, the mean lateral Webber number \( \overline{W_e} \), and the dimensionless term \( [\pi d_s^3 ] \frac{\Delta t}{A_s \Delta d} \) that proportional to collision probability were estimated in order to analyze the distribution behavior of the observed \( P.P. \).

For fully-developed water impinging sprays, \( P.P. \) increased from 54% to a maximum of 61% at lower momentum rates \((4000 \text{ g} \cdot \text{cm}^2/\text{s}^2 ~7500 \text{ g} \cdot \text{cm}^2/\text{s}^2)\) that was mainly caused by the decrease of the collision probability between droplets. At the conditions, low \( \overline{W_e} \) would result in coalescence when droplet collides. At higher momentum rates \((7500 \text{ g} \cdot \text{cm}^2/\text{s}^2 ~14000 \text{ g} \cdot \text{cm}^2/\text{s}^2)\), the pattern of off-centre separation or stretching separation from droplet collisions at higher \( \overline{W_e} \) reduced the ability of suppressing \( P.P. \) by droplet collision, thus a gradual increase of the \( P.P. \) occurred.

Similar results were also observed for the impingements of acetone-water solution with lower surface tension. However, the values of \( P.P. \) in acetone-water sprays were always greater than that in water sprays due to the effects of lower collision probability and higher \( \overline{W_e} \). The analyses showed that the complicate mixing behavior of impinging spray at fully developed conditions were mainly controlled by the collision probability of droplets and Webber number of droplet lateral motion, that is, the interactions between droplets in the spray.

**Nomenclature**

- \( A_s \) : distribution areas of droplets
- \( b \) : impact parameter
- \( d \) : downstream distance from impinging point
- \( d_{32} \) : Sauter mean droplet size
- \( \overline{d}_{32} \) : averaged Sauter mean droplet size
- \( \overline{m}_d \) : averaged droplet mass
- \( M_p \) : liquid mass of one jet moving toward the other side
- \( M_d \) : total droplet mass
- \( n \) : number density in the control volume
- \( N_t \) : total droplet number in the control volume
- \( P \) : collision probability of droplets
- \( P_m \) : the probability at the lateral position \( x \) of PLIF
- \( v_{jet} \) : jet velocity
- \( v_s \) : lateral velocity of droplet
- \( \overline{v}_s \) : weighted mean lateral velocity of the spray
$V$ control volume

$w$ the width of the spray fan at certain cross-section

$We$ Webber number

$We_x$ mean lateral Webber number of the droplets

$x$ lateral distance to the impinging center line

$Z$ droplet collision rate

$\rho$ density of liquid

$\sigma$ surface tension

$\theta$ spray angle

$\Delta t$ time for spray to travel through the control volume

$\Delta d$ a fixed value of 1mm

$P.I.$ patternation index

$E_m$ mixing efficiency

$P.P.$ penetration percentage

References


Table 1. Physical properties of the test liquids

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<th>acetone (vol.%)</th>
<th>density, $\rho$ (g/cm$^3$)</th>
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Table 2. Experimental conditions and results of the water doublet impinging jets

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<th>jet velocity (m/s)</th>
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<th>(P.I.)</th>
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Table 3. Experimental conditions and results of the acetone-water doublet impinging jets rates

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Figure 1. Schematic of the nitrogen-compressed flow control system.

Figure 2. Definition of spray angle $\theta$.

Figure 3. 2-D mass probability distribution of the liquid from the left-side jet in the PLIF observations (orifice: $\varphi$ 0.3mm, impinging angle: $\pm 30^\circ$)
Figure 4. Definition of the penetration percentage (P.P.)

Figure 5. The penetration percentages and mixing efficiencies at different downstream positions

Figure 6. The variation of the penetration percentages with jet’s momentum rate for the doublet impinging sprays of water

Figure 7. The variation of the penetration percentages with jet’s momentum rate for the doublet impinging sprays of acetone (10 vol%) in water solution
Figure 8. Front-view images of water impingements at open-rim ($m\nu \sim 1455\ g\cdot cm/s^2$) and fully-developed conditions ($m\nu \sim 17162\ g\cdot cm/s^2$).

Figure 9. The variation of the spray angles ($\theta$) with jet’s momentum rates for the water doublet impinging sprays.

Figure 10. The averaged SMD ($\bar{d}_{12}$) at different momentum rates measured at 15mm downstream from the impinging point.

Figure 11. The mean lateral velocities ($\bar{V}_y$) at different momentum rates estimated measured at 15mm downstream from the impinging point.
Figure 12. The Webber numbers of the droplets in lateral motion at different momentum rates estimated at 15mm downstream from the impinging point.

Figure 13. The areas of droplet distribution at different momentum rates measured at 15mm downstream from the impinging point.

Figure 14. The variation of the dimensionless term $\left( \frac{\Delta t}{\tau_2} \right) \frac{dA}{dx}$ with momentum rate estimated at 15mm downstream from the impinging point.