Experimental Investigation of Droplets Characteristics after the Trailing Edge at Different Angle of Attack

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ABSTRACT

Inlet fogging of gas turbines has been commonly adopted for the power augmentation of gas turbines. The major benefits of this method are; increase in power output and reduction of NOx levels. This paper covers the results of extensive visualization and experimental studies conducted to understand the phenomena of droplets breakup at different flow conditions. Experimental study of the behaviour of ligament breakup and droplets size distribution is addressed from 0-degree to 10-degree angle of attack. Image processing method was utilized for the measurements of droplets size distribution after the trailing edge of the blade. It is found that the droplets size distribution is governed by the dominance effects of aerodynamics and surface tension forces, and remains the same at a specific position after the trailing edge region. Also, droplets size increases with an increase in blade’s angle of attack and a decrease in air momentum.

NOMENCLATURE

Latin Symbols

- \( D \) diameter, m
- \( U \) velocity, m/sec
- \( t \) thickness of the T.E. of the blade, m
- \( \dot{m} \) mass flow rate, kg/sec
- \( C \) chord length, m
- \( A \) area, m²
- \( P \) perimeter, m
- \( x,y \) x- and y- axis directions

Greek Symbols

- \( \rho \) density, kg/m³
- \( \mu \) dynamic viscosity, N.sec/m²
- \( \sigma \) coefficient of surface tension, N/m

Subscripts

- \( l \) liquid
- \( a \) air
- 10 D10 (or average) diameter, m
- 32 D32 (or Sauter mean) diameter, m

Dimensionless Numbers

- \( Re \) Reynolds Number of air \((\rho_a U_c C/\mu_a)\)
- \( MFR \) Dimensionless mass flow rate \((\dot{m}/\mu_a C)\)
- \( We_a \) Weber number based on T.E. \((\rho_a U_a^2 t/\sigma)\)
- \( M \) Momentum ratio \((\rho_a U_a^2/\rho_l U_l^2)\)

INTRODUCTION

Gas turbines (GT) are one of the most important thermal energy devices, due to their wide range of power output ranging from few kilo-watts (kWs) to mega-watts (MWs). It is generally known that the large amount of the GT output is utilized to run the compressor. Additional power losses occur if the GT are operated at high ambient atmospheric conditions. Kakaras et al. [1] showed that for an ambient temperature of 40°C and relative humidity of 45%, the thermal efficiency and power output decreases by 1.66% and 14.48% respectively. Humidified GT using the air-water mixture as the working fluid have been identified to have the potential of augmenting the power output of GT by reducing the compressor load. Water ingestion techniques are considered as a new technique which has been recently adopted in industrial GT systems. Different water ingestion techniques are proposed to boost GT power output, however, the most liked technique among the GT manufacturers is inlet fogging, because of being simple and easy to install. Potential thermodynamic advantages of fogging have been understood and studied by many researchers [2, 3]. Most of these studies are mainly focused in understanding effect of water injection on the overall performance of the GT systems. However, seldom studies about the droplets motion and breakup occurring in the flow are published. Based on inlet fogging technique, Advanced Humid Air Turbine (AHAT) systems have been proposed, as shown schematically in Fig. 1. One of the distinctive features of the AHAT system is their faster start-up time compare to that of ordinarily combined cycle (C.C.) system [4]. Additionally, the power degradation of AHAT systems at high temperature is also less compared to the C.C. systems [4].

In spite of the fogging being a popular augmentation method, there is a scarcity of experimental visualization and droplets measurement data. This paper along with the Part I is expected to understand the fundamental kinematics of liquid film and droplets formation as well as their breakup under different flow regimes. This paper provides the results of extensive experimental studies conducted to understand the droplets characteristics around a cascade blade in a humid air. The main focus of this study is to understand the droplets size distribution

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after the trailing edge (T.E.) of the blade by performing experiments in a specially designed wind tunnel.

Droplets Effects in Turbine Systems:

Figure 2 shows the schematics of droplets ingestion in a GT system. Fine water droplets are injected into the inlet plenum of the GT which continue to flow along the air flow Droplets upon colliding with the blades result in the formation of the liquid film onto the blade’s surface, which continues to flow towards the T.E. of the blade. At the T.E. of the blade, water start to accumulate due to the surface tension of the liquid. Once the aerodynamic forces exceed the surface tension force, coarse droplets are formed from the T.E. The shedding frequency and the size of coarse droplets formed depends on the aerodynamic surfaces as well as the liquid’s surface tension. The aerodynamic forces act to drive and disintegrate the droplets whereas the surface tension act to retain the droplet to retain its original shape and position. The coarse droplets formed after the T.E. are highly undesirable as they can lead to the erosion phenomenon. Moreover, due to their large size, these coarse droplets possess relatively high momentum, which leads to the permanent dents on to the rotor blades due to the continuous bombardment. Bigger droplets are easily captured by the blades and can form liquid film, Fig. 3. On the other hand, smaller droplets are affected by the aerodynamic forces and may pass through the blades row, as shown in Fig. 3. As the droplets size increases more energy would be required from the main flow to accelerate them, which may ultimately lead to the reduction of the overall efficiency of the GT system.

EXPERIMENTAL SETUP

Figure 4 shows the experimental layout used in the present study. Air flow through the facility is driven by a centrifugal blower located at the upstream position of the test section. Centrifugal blower is followed by the settling chamber. Inside the settling chamber a perforated plate was fixed to reduce the freestream turbulence intensity of the incoming flow. After passing the settling chamber, air finally reaches the test section. The cross section of the test facility is 80 x 100 mm². Water is supplied directly to the test blade via a water tank, whose mass flow rate was controlled by adjusting the height of water inside the water tank. At the end of the test section, a droplet stopper and collector setup was placed to stop the droplets splashing downstream, and are collected in a water bucket from where water is drained off. Backlighting technique was used to capture the high-speed images, as shown in Fig. 4. The shadowgraph images were captured in the after T.E. region as represented by the blue colour in Fig. 4.

Test Blade:

An elliptical profile blade was used as a test blade to understand the characteristics of droplets disintegration at different positions after the T.E. of the blade, as shown in Fig 5. Unlike, real turbomachines, water was ejected from inside the 1 mm diameter hole located at the mid-span of the L.E.. Water ingestion by this method not only simplifies the fundamental phenomena involved in the droplets formation but also the role of the ingestion hole and the effect of T.E. thickness on to the droplets characteristics formed after the T.E. region can also be study with ease. Table 1 gives the detail specification of the different parameters of the blade profile. The blade used in the present study is made of aluminium having a span and chord length of 80 mm and 50 mm respectively.

Flow Conditions:

Table 2 summarizes the flow conditions under which experiments are performed in this study. The maximum
achievable velocity inside the wind tunnel was 40 m/sec, whereas, the lowest velocity used was 20 m/sec. Air velocities (without blade) in the tunnel were measured by using a single element hot-wire. The maximum uncertainty measured by the hot-wire without inserting blade in the test section was under 2%. Figure 6 shows the velocity distribution after the T.E. region of the blade measured at 0- and 10 - degree. Similar, velocity distributions were also calculated for the other AOA as mention in Table 2. In Fig. 6, black, red, blue and violet colour lines correspond to Case A, Case B, Case C and Case D respectively. Similarly, the filled and unfilled round symbols represent the velocity data measured at 0.25- and 1-C positions after the T.E. As expected, due to the symmetric blade profile the wake profile was also symmetric with a large velocity deficit just behind the aerofoil, as shown in Fig. 6 (a). A velocity deficit of around 25%, 20%, 18% and 15% occurred for the Case A, Case B, Case C and Case D respectively at 0.25-C position, which diminished gradually as the distance after the T.E. increases. As the AOA is increased to 10 - degree (Fig. 6 (b)), the velocity deficit after the T.E. of the blade also increases due to the low velocity region caused by the flow separation. Room temperature water was used as a working liquid, whose dimensionless mass flow rate is calculated by Eq. (1)

\[
MFR = \frac{\dot{m}_l}{\mu l C}
\]  

(1)

**Image Acquisition and Processing:**

Photon FASTCAM APX-RS was used as a high-speed camera (HSC) to capture the high-speed images. The backlighting technique was utilized by placing two light sources, each 250W to capture the shadowgraph images. For image acquisition, the imaging rate was chosen as 1000 frames per seconds (fps) with a shutter speed of 1/15,000 seconds (sec). With these settings, the camera resolution was set as 1024 x 1024 sq. pixels (80 x 80 mm² approx.).

**Table. 1 Specifications of elliptical profile blade**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Chord length (C)</td>
<td>50 mm</td>
</tr>
<tr>
<td>Span length (S)</td>
<td>80 mm</td>
</tr>
<tr>
<td>Thickness ratio of the blade at mid-chord</td>
<td>15 %</td>
</tr>
<tr>
<td>T.E. thickness ratio</td>
<td>4.5 %</td>
</tr>
<tr>
<td>Water ingestion hole</td>
<td>ϕ1 mm</td>
</tr>
<tr>
<td>T.E. thickness</td>
<td>2.25 mm</td>
</tr>
</tbody>
</table>

**Table. 2 Experimental flow conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Velocity (m/sec)</td>
<td></td>
</tr>
<tr>
<td>Reynolds Number (Re)</td>
<td></td>
</tr>
<tr>
<td>High Air Velocity</td>
<td>Case A 40 1.35 x 10^5</td>
</tr>
<tr>
<td>Medium Air Velocity</td>
<td>Case B 30 1.01 x 10^5</td>
</tr>
<tr>
<td></td>
<td>Case C 25 0.82 x 10^5</td>
</tr>
<tr>
<td>Low Air Velocity</td>
<td>Case D 20 0.67 x 10^5</td>
</tr>
<tr>
<td>Angle of attack (AOA)</td>
<td>0-, 3-, 5-, 7-, 10- degrees</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>298.5 K (approx.)</td>
</tr>
<tr>
<td>Water temperature</td>
<td>Room water temperature</td>
</tr>
<tr>
<td>Dimensionless mass flow rate (MFR)</td>
<td>2 – 32</td>
</tr>
<tr>
<td>Air density</td>
<td>1.23 (kg/m³)</td>
</tr>
<tr>
<td>Water density</td>
<td>1000 (kg/m³)</td>
</tr>
</tbody>
</table>

For image processing, an in-house code was made based on the canny edge detection method [11]. Figure 7 shows the image conversation from a shadowgraph image (Fig. 7 (a)) to the binary image (Fig. 7 (b)). It should be noted that the droplets having diameter less than 5 pixels were deleted from the analysis to avoid any uncertainty which might have caused during the binarization of the shadowgraph images.
EXPERIMENTAL RESULTS AND DISCUSSIONS

Classification of ligaments breakup and droplets formation:

Ligaments breakup and the droplets formation after the T.E. of the blade is classified based on the dimensionless momentum ratio and weber number (based on the T.E. thickness) as expressed mathematically by Eq. (2) and (3) respectively.

\[ M = \frac{\rho_a U_a^2}{\rho_l U_l^2} \]  \hspace{1cm}  (2)

\[ We_a = \frac{\rho_a U_a^2 t}{\sigma} \]  \hspace{1cm}  (3)

Figure 8 and 9 shows that air momentum clearly dominates the breakup phenomena. After extensive visualization, the breakup of ligament and the droplets formation after the blade is categorized due to the dominant effects of the following two forces.

i. Dominant Aerodynamic Forces: It was shown in the Part I of this paper that for high air momentum, surface waves appeared on the blade’s surface. The momentum of these high-speed waves plays an important role in the disintegration of ligaments from the T.E. [12]. At 0 – degree, Fig. 8 (a), the high-speed surface waves were occasionally seen to break off directly from the T.E. rather than accumulating at the T.E. However, accumulation of these high speed waves was also observed to transfer their momentum to the already accumulated water at the T.E.. When accumulated water at the T.E. reaches a critical amount, the vortex shed from the T.E. (mostly from the lower surface (pressure side (P.S.)) of the blade causes destabilization of accumulated water, leading to the shedding of a large chunk of accumulated water after the T.E. region. The accumulated water was also seen to moves upwards towards the upper surface (suction side (S.S.)) and the vortex shed from the S.S. further enhances the droplets formation phenomenon by stripping a large number of droplets as well as moved the accumulated water downwards. This process continues until enough amount of water in the form of droplets is shed off from the T.E.. Due to surface stripping, occasionally relatively big droplets were also formed in the near vicinity of the T.E. and soon underwent bag mode of a breakup [13] (see appendix). However, from the visualized images majority of the droplets formed were due to the vibration mode of the breakup. When the AOA was gradually increased, relatively large amount of water got accumulated at the T.E. (Fig. 8 (b) and 8 (c)), due to

![Shadowgraph image with water ingestion](image1)

(b) Binary image

Fig. 7 Binary image generation

![Instantaneous images of ligament breakup and droplets fragmentation after the T.E. of the blade (Air velocity 40 m/sec, $M \approx 192, We_a \approx 60$) – Breakup due to the dominant aerodynamic forces](image2)

![Instantaneous images of ligament breakup and droplets fragmentation after the T.E. of the blade (Air velocity 20 m/sec, $M \approx 48, We_a \approx 15$) – Breakup due to the dominant surface tension forces](image3)
the flow separation. Due to the relatively large amount of accumulated water, a large number of droplets were formed due to the breakup of ligaments by the vortex shedding. From Fig. 8, as the AOA was increased, the relative ligament length as well as the number of droplets formed also increases. In general, most of the droplets formed in this case were due to the vibrational mode of the breakup of ligament or droplets, however, with increasing AOA the occurrence of ligaments bag breakup also increases slightly due to the penetration of vortex into the thick ligaments, as shown in Fig. 8 (b) and 8 (c).

ii. Dominant Surface tension Forces: For low air momentum, a completely different type of ligament breakup and droplets disintegration occurred, as shown in Fig. 9. The waves formed in this case were mirror-like smooth (see Part I) and did not actively contribute to the breakup of ligaments, rather resulted in the accumulation of water at the T.E.. Due to the dominant surface tension forces, the vortex shedding from the T.E. only oscillates the accumulated water to and fro about the T.E. position. When the accumulated water reached a certain limit, and became almost perpendicular to the incoming air flow, Fig. 9 (b), the vortex shed resulted in the formation of very large and elongated ligaments, which broke up due to the bag mode, as shown in Fig. 9. For this case too, with incrementing AOA the amount of water accumulation due to flow separation increases. It was also observed from the high-speed images that with increasing AOA the point of ligament formation further moved upward on the S.S. of the blade, such that even the ligament broke up (due to the bag mode) with its base remained attached at the upper surface of the blade, as shown in Fig. 9 (b) and 9 (c).

Table 3 summarizes in detail the droplets breakup events for 0 – degree AOA case at different positions after the T.E. of the blade.

### Table 3 – Summary of droplets breakup at 0 – degree AOA

<table>
<thead>
<tr>
<th>Case</th>
<th>Position after the T.E.</th>
<th>High Momentum ratio (Case A)</th>
<th>Low Momentum ratio (Case D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Velocity 40 m/sec</td>
<td>0 to 0.25-C</td>
<td>0.25-C to 0.5-C</td>
<td>0.5-C to 0.75-C</td>
</tr>
<tr>
<td>$M \approx 192$</td>
<td>• Wave stripping.</td>
<td>• Frequent vibrational breakup.</td>
<td>• Occasional vibrational breakup.</td>
</tr>
<tr>
<td>$We_a \approx 60$</td>
<td>• Coarse droplets (if formed) undergo bag breakup.</td>
<td>• Occasional start of a vibrational breakup.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Ligament length usually within this range.</td>
<td>• Ligament length just under this range.</td>
<td>• Ligament length just under this range.</td>
</tr>
<tr>
<td></td>
<td>• Occasional bag breakup of the ligament.</td>
<td>• Coarse droplets formed.</td>
<td>• Occasional start of a vibrational breakup.</td>
</tr>
<tr>
<td></td>
<td>• Usually no breakup but frequently thick elongated ligament only.</td>
<td>• Occasional bag breakup of the ligament.</td>
<td>• Occasional bag breakup of the ligament.</td>
</tr>
</tbody>
</table>

In the present study, D10 and D32 droplets representative

![Diagram of droplets size measurement positions after the T.E. of the blade](image_url)

Fig. 10 Droplets size measurement positions after the T.E. of the blade
diameters are used, which represents the average and Sauter mean diameter (SMD) droplets size distribution respectively of a spray system. Figure 11, 12 and 13 shows the experimentally measured droplets size for an AOA of 0-, 5- and 10- degrees respectively, at various liquid flow rate (MFR) conditions. Here the filled and unfilled round symbols correspond to the D10 and D32 droplets size distribution respectively. Black, red, blue and purple colour represents the droplets measuring positions at 0.25-, 0.5-, 0.75- and 1-C positions whereas, the dotted lines represents the corresponding mean droplets size at the above-mentioned positions. From Fig. 11 (a), the D10 and D32 droplets size distribution remains unchanged, whatever the

**Fig. 11 Droplets size distribution after the T.E. region (AOA – 0 degree)**

**Fig. 12 Droplets size distribution after the T.E. region (AOA – 5 degrees)**

**Fig. 13 Droplets size distribution after the T.E. region (AOA – 10 degrees)**
liquid’s mass flow rate. This is mainly due to the fact that once the droplet detached from the T.E., then the droplet size is governed by the slip velocity between the surrounding air and droplet. As the slip velocity between the droplet and surrounding air is a function of the liquid’s surface tension property and the air velocity (which remained constant in our study) resulting in almost similar droplets size. It is due to this reason a change in liquid’s flow rate does not affected the droplets size distribution at each of the above measured positions after the T.E. of the blade. However, an increase in liquid’s flow rate resulted in the formation of a large number of droplets. As the distance after the T.E. increases, the droplets breakup results in a decrease in the droplets size, as shown in Fig. 11. For a high momentum ratio, Fig. 11 (a), the droplets size distribution at any position is less than that of the low momentum ratio case, Fig. 11 (c). This is mainly due to the greater energy transfer between the liquid and the gaseous phases, resulting in the generation of smaller droplets for high momentum ratio (Case A – Fig. 11 (a)) compared to that of the low momentum case (Case D – Fig. 11 (c)). A similar phenomenon was observed for the droplets size distribution at 5- and 10-degrees AOA case, as shown in Fig. 12 and 13 respectively. However, the droplets size became marginally larger under the similar conditions with an increase in the AOA of the blade due to the reduced velocity effects after the T.E. region. At high momentum ratio near the T.E. (0.25-C), droplets can be seen to deviate more compare to the other positions after the T.E. region, which was due to the presence of longer ligaments length as well as the high non-circularity of the droplets. The droplets shed from these ligaments also get deposited on the side walls of the test section, which also resulted in the large deviation. Though, large number of these wall droplets were removed in the binary code, however, there remained few which may have caused such large discrepancy in

![Fig. 14 Circularity of droplets aft the T.E. (AOA – 0 degree)](attachment:image)

![Fig. 15 Droplets size frequency and cumulative volume distribution @ MFR ≈ 9.0 (AOA – 0 degree)](attachment:image)
the measured results.

Figure 14 shows the perimeter ratio of actual droplets to that of a circle (possessing the same area as that of the droplet) at 0.25-C and 1-C for the selected flow rate of liquid for Case A and Case D at 0–degree AOA and is calculated mathematically as expressed by Eq. (6)

$$\text{Perimeter ratio} = \frac{P_{\text{droplet}}}{\sqrt{4\pi A}}$$ (6)

In the above equation, the perimeter of any bounded area (i.e. droplet) was calculated by using a distance function in two dimensional euclidean plane, expressed mathematically by

$$P_{\text{droplet}} = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}$$ (7)

Relatively large number of non-circular droplets for the high momentum ratio case were measured near the T.E., however, as the distance after the T.E. increases the droplets became more spherical, as shown in Fig. 14 (a). This is due to the dominant effects of high aerodynamic forces, making droplets to elongate more near the T.E. (0.25–C) compare to their respective circular diameter. However, as the distance after the T.E. increases (1–C) droplets tend to become more spherical due to the breakup of droplets as well as an increase in the dominant effects of the liquid’s surface tension forces. These droplets reach a stage when they no longer underwent further breakup and became relatively more spherical, as shown in Fig. 14 (a). For low air momentum case, (Case D – Fig. 14 (c), the droplets retain their circularity due to the dominance effect of liquid’s surface tension, and it is probably due to this reason droplets also did not deviate near the T.E., as shown in Fig. 11 (c).

Figure 15 shows the droplets number fraction and cumulative distribution for different cases under the same ejection flow rate of the liquid for the Case A and D at 0 – degree. From Fig. 15, as the distance after the T.E. region increases, the number of droplets generated also increases due to the breakup of droplets. For high momentum cases (Fig. 15 (a)) the droplets formed at

\[\text{small gradient of droplets size change near the T.E. (Bag Breakup, Ligament Breakup)}\]
\[\text{Large gradient of droplets size change near the T.E. (Bag Breakup)}\]
\[\text{Large gradient of droplets size change near the T.E. (Vibrational Breakup)}\]
\[\text{Large gradient of droplets size change near the T.E. (Mainly Bag Breakup)}\]

Fig. 16 Effect of AOA on average (D10) droplets size distribution after the T.E.
0.25-C were nearly 6,000 in numbers which increased by almost 3 times to 18,000 as the distance after T.E. increases to 1 C. However, for low momentum cases (Case D – Fig. 15 (b)), the number of droplets surge to nearly eightfold from approximately 1,000 to 7,500 as the distance increased from 0.25-C to 1-C. This rapid increase in the number of droplets resulted from the bag mode of the breakup of ligaments and droplets when exposed to the surrounding high aerodynamic forces (see bag breakup image in the appendix). Though, from the experimental results, it is found that the number of droplets not necessarily increase by the above mention factor. Overall, the droplets fraction increases for low air momentum cases is always larger than that of the high air momentum cases, under the similar condition of liquid flow rate. High air momentum cases undergo frequently vibrational mode of a breakup, resulting in overall small change in droplets size, as shown in Fig. 15 (a). On the other hand, low air momentum cases (Case D – Fig. 15 (d)) underwent mainly bag breakup, which resulted in a drastic change in the droplets size as the distance after the T.E. increases.

Figure 16 and 17 summarizes the D10 and D32 droplets size distribution for different AOA for a fixed air momentum case. Due to the lessening in aerodynamic forces, the droplets size near the T.E. increases with an increment in AOA. In the case of high air momentum cases (Case A) the gradient of droplet size change remains essentially the same as the distance after the T.E. region increased, Fig. 16 (a), by the virtue of the vibrational mode of a breakup. Though, with increasing AOA the occurrence due to bag mode of droplet breakup do increased marginally but overall the gradient of droplets size change remains nearly the same. The average droplet size (D10) change for 0-degree at 1-C (with-respect-to 0.25-C) decreases marginally (about 17%) which also remains almost the same for the 10-degree case. When the air momentum is increased slightly (Case B and Case C), the gradient of droplet also decreases significantly near the T.E., as shown in Fig. 16 (b) and

![Diagram](image1)

(a) Case A (Air velocity – 40 m/sec)  
\( M \approx 192, We_a \approx 60 \)

![Diagram](image2)

(b) Case B (Air velocity – 30 m/sec)  
\( M \approx 108, We_a \approx 34 \)

![Diagram](image3)

(c) Case C (Air velocity – 25 m/sec)  
\( M \approx 75, We_a \approx 23.45 \)

![Diagram](image4)

(d) Case D (Air velocity – 20 m/sec)  
\( M \approx 48, We_a \approx 15 \)

Fig. 17 Effect of AOA on sauter mean diameter (D32) droplets size distribution after the T.E.
SUMMARY AND CONCLUSIONS

Experimental investigations were conducted to understand the droplets size distribution after the T.E. of the blades at various AOA (0- to 10-degree). It is expected that this fundamental study would lead to the further understanding of the droplets disintegration phenomena in the humid turbine systems. From the context of this study, following conclusions are drawn:

- Droplets size distribution after the T.E. region is governed by the air momentum and the angle of attack, whereas it is independent of the liquid’s mass flow rate.
- The droplets size increases with an increase in the angle of attack, due to a decrease in the local air momentum after the T.E. region.
- At a particular value air of momentum and angle of attack the droplets size after the T.E. remains identical at a particular position due to the same slip velocity between the gaseous and liquid phases.
- For high air momentum ratio the droplets undergo breakup primarily due to the aerodynamic forces whereas for low momentum ratio the breakup is governed by the liquid’s surface tension.
- With an increase in the angle of attack of the blade, the gradient of droplets size change moves slightly away from the T.E., and is more affected for the low momentum cases.
- Droplets circularity near the T.E. is affected more at high momentum ratio than at low momentum ratio due to high energy transfer from the gaseous phase to the liquid phase. This results in the relatively large deformation of the droplets and ligaments near the T.E.
- For the same angle of attack conditions, the droplets formed for high air momentum ratio is always smaller in size than that of the low momentum ratio at any position.

REFERENCES

APPENDIX

Figure A shows the detail schematics of different modes of droplets breakup. For more study, readers are requested to reference [13] for to understand the characteristics of droplet deformation and breakup regimes.

Air Flow

- **Deformation & Flattening** (We < 12)
  - ![Deformation & Flattening](image1)

- **Vibration Breakup** (We ≈ 12)
  - ![Vibration Breakup](image2)

- **Bag Breakup** (12 ≤ We ≤ 50)
  - ![Bag Breakup](image3)

- **Bag & Stamen Breakup** (50 ≤ We ≤ 100)
  - ![Bag & Stamen Breakup](image4)

- **Sheet Stripping** (100 ≤ We ≤ 350)
  - ![Sheet Stripping](image5)

- **Wave Crest Stripping** (We ≤ 350)
  - ![Wave Crest Stripping](image6)

- **Catastrophic Breakup** (We ≤ 350)
  - ![Catastrophic Breakup](image7)

Fig. A Droplet deformation and breakup regimes [13]

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