Effect of trailing edge size on the droplets size distribution downstream of the blade

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Abstract
Operational flexibility, such as fast start-up time, ability to adapt to the load change as well as high efficiency has made the gas turbines as one of the most important energy devices among the thermal power systems. It is well-known that gas turbines efficiency decreases with an increase in the ambient atmospheric temperature. For that purpose, recently fogging of water droplets have been utilized to increase the power output of these industrial gas turbines. Based on fogging principle, Advanced Humid Air Turbines (AHAT) are developed which utilizes the humid air to increase the thermal efficiency of the gas turbine systems. In this paper, the characteristics of the humid air system are investigated experimentally. Extensive high-speed images were taken using a high-speed camera. Analytical models are proposed based on the mass and energy conservation principle to understand the effects of the thickness of the trailing edge of the droplets size distribution after the trailing edge of the cascade blades. From the proposed model and experimental data, it is found that the primary droplets formed are inversely proportional to the Weber number (based on the blade thickness). It is also concluded that if the Weber number of the two profiles were kept constant, then the one with greater trailing edge thickness would result in larger primary droplet size and vice versa.

Keywords : Gas turbine, Fogging, Trailing edge thickness, Water sheet primary breakup, Shadowgraph images

1. Introduction

Gas turbines (GT) have been used in fulfilling the peak power load demands due to their ability to adapt to the load changes quickly. In fact, they have become vital devices for power augmentation. Their use in combined cycle (C/C) systems have helped in increasing the overall efficiency and work output of the thermal power plants. It is well-known that the GT performance are greatly influenced by the altitude, ambient temperature and the inlet mass flow to the compressor. Generally, GT are rated at the standard conditions of temperature and pressure at sea level. However, in most circumstances GT are not operating at these standard conditions due to which their performance differs from that of the design ratings. For that purpose various techniques have been proposed in improving the overall performances of these systems by reducing the inlet temperature of the compressor. Lower compressor inlet temperature can be accomplished by installing a chiller, as shown in Fig. 1 (a). Similarly, the inlet temperature can be reduced by allowing the air to flow through the evaporative cooler, as shown in Fig. 1 (b). However, the technique mostly preferred by the GT manufacturers is the fogging technique, Fig. 1(c), primarily due to its simplicity in installation. After a careful inspection of various power augmentation systems, Bhargava and Meher-Homji (2002) concluded that the overall cost of the fogging technique is almost five times lower compared to the other power augmentation techniques. Similarly, according to Meher-Homji and Mee (1999), fogging can not only increase the thermal efficiency of a simple GT systems but they can also be effectively used with the C/C systems, which is not the case for the other inlet air cooling techniques. Mitsubishi Hitachi Power Systems (MHPS) had proposed Advanced Humid Air Turbines (AHAT) systems,
which operates primarily on the fogging systems. The distinguishing feature of AHAT systems is the ingestion of humidified air due to the ingestion of fine droplets from the high-pressure nozzles. The presence of these droplets greatly augments the power output of the systems as discussed by Araki et al. (2012). Due to the presence of the water droplets in the air, the inlet density of the incoming air into the compressor is increased, resulting in reducing the compressor work and overall increase in the system performance.

Recently, much attention has been made to understand the overall effect of the fogging system on the performance of GT systems. According to Hatamiya et al. (2007), the efficiency of AHAT cycles is about 5% higher compared to that of the middle-sized combined cycles with no reheat, whereas, an increase of 10% efficiency is obtained when compared to the Heat Recovery Steam Generator (HRSG) with the same core engine. Utamura et al. (1999) had shown that an overspray of 1% can result in an increase of power output and thermal efficiency by 10% and 3% respectively for a 115 MW GT (Hitachi Frame 9E). Gotoh et al. (2011) discussed the benefits of water droplet ingestion systems in AHAT systems, which are expected to achieve higher efficiency without increasing the pressure or combustion temperature. Sun et al. (2012) used a 3D model of an entire gas turbine to calculate the effects of water ingestion. They reported that water ingestion leads to an increased mass flow and power output as well as a higher compressor efficiency. They also identified an improvement in the flow separation behaviour on the first stage of the compressor. Burn et al. (2006) found that wet compression can result in a displacement of the operating point towards the surge line. However, according to authors knowledge fewer experimental research studies have been conducted to understand the physics of droplets accumulation and formation downstream of the T.E. region. Therefore, the main objective of our research study is to understand the droplets characteristics in a cascade system.

The schematics of the two-phase phenomenon in a cascade system can be understood as illustrated in Fig. 2. The incoming water droplets from the high-pressurized nozzles strike near the leading edge (L.E.) of the compressor blade. The droplets which strike the blade is deformed by forming a thin sheet of water film onto the blade’s surface. A rivulet region is formed at the downstream of the thin film region, which continues to flow towards the trailing edge (T.E.) of the compressor blades by the influence of the aerodynamic forces. At the T.E. the individual droplets recombined to
form larger globules. These globules remained attached to the T.E. due to the influence of the surface tension of the liquid but grow in the direction of the airflow and along the span-wise direction at T.E.. As the globules size increases, the aerodynamic force acting to tear the globules also increases, resulting in the breakup of large droplets from the edge of the T.E.. The shedded droplets are relatively larger in size compared to those ingested from the high-pressurized nozzles, as shown schematically in Fig. 2. Due to their large size and density, more energy would be required from the main flow to accelerate them. These large droplets cause erosion as well as possess high momentum which may lead to a physical damage to the rotor blades. Therefore, it is highly desirable to understand and analytically predict the characteristics of the shedded droplets to optimize the droplets size ingestion from the nozzles. In our previous researches, Javed et al. (2015), the authors had conducted detailed experimental studies and concluded that the liquid’s mass flow rate did not contribute significantly to the droplets size formed after the T.E. of the blade. In the other study, Javed et al. (2016), we had proposed various analytical models to predict the characteristics of the liquid sheet disintegration from the T.E. of the blade. According to authors knowledge, almost no paper has been published so far which not only consider the effect of T.E. thickness but also give analytical expression of its effect on the droplet size distribution. Therefore, the aim of the present study is to understand the role of the T.E. thickness on the droplets size formation and the corresponding droplets size distribution after the T.E. of the cascade blade.

2. Experimental Setup

2.1 Test Facility

A two-phase wind tunnel is designed and manufactured to understand the kinematics of the two-phase phenomenon

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Material</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Number of aerofoil in cascade</td>
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<tr>
<td>Chord Length (C)</td>
<td>50 [mm]</td>
</tr>
<tr>
<td>Span length (S)</td>
<td>80 [mm]</td>
</tr>
<tr>
<td>Maximum thickness</td>
<td>7.5 [mm]</td>
</tr>
<tr>
<td>Thickness ratio</td>
<td>15 [%]</td>
</tr>
<tr>
<td>Hole diameter (for injecting water)</td>
<td>3 [mm]</td>
</tr>
<tr>
<td>Hole diameter (L.E.)</td>
<td>1 [mm]</td>
</tr>
<tr>
<td>Trailing Edge Thickness (t)</td>
<td>2.25 [mm]</td>
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</table>

Table 2 – Flat profile blade specifications

<table>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Material</td>
<td>Brass</td>
</tr>
<tr>
<td>Number of aerofoil in cascade</td>
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</tr>
<tr>
<td>Chord Length (C)</td>
<td>50 [mm]</td>
</tr>
<tr>
<td>Span length (S)</td>
<td>80 [mm]</td>
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<tr>
<td>Maximum thickness</td>
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</tr>
<tr>
<td>Thickness ratio</td>
<td>12 [%]</td>
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<tr>
<td>Hole diameter (for injecting water)</td>
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<tr>
<td>Hole diameter (L.E.)</td>
<td>1 [mm]</td>
</tr>
<tr>
<td>Trailing Edge Thickness (t)</td>
<td>6 [mm]</td>
</tr>
</tbody>
</table>

Fig. 4 Test blades configuration
around a cascade blade, as shown in Fig. 3. The test section is equipped with the test blade. Centrifugal blower is used to supply air to the test section. Before air reaches the test section, it passes through the settling chamber, followed by the nozzle and the honeycomb section. The test section is followed by the diffuser, allowing the air to expand smoothly downstream of the test section. A water tank is used to supply water directly to the test blade. In order to avoid the splashing of water droplets downstream of the test facility, a droplet stopper and collector setup are placed to stop the moving droplets, which are then collected in a water bucket and finally drained off. More details of the experimental facility and the water supply system can be found in our previous studies, Javed et al. (2015).

2.2 Test Blades

Two simple cascade blade geometries are used to understand the kinematics of two-phase phenomenon in the humidified GT systems, as shown in Fig. 4. The curvature of the suction side (S.S.) and pressure side (P.S.) of the blades correspond geometrically to the elliptical and the flat profile, and hence are named as the Elliptical and Flat profile blade, as shown in Fig. 4 (a) and 4 (b) respectively. The aim of using different profile geometries is to grasp the influence of the T.E. size and shape on the droplets size distribution downstream of the blade’s T.E.. Detail specifications of both blade profiles are given in Table 1 and Table 2. Both blade profiles have an identical chord length and the span length of 50mm and 80mm respectively. The T.E. thickness of the elliptical profiled blade is equivalent to the twice distance between the focus and the vertex on the major axis of the blade. On the other hand, flat profile blade’s T.E. thickness is equivalent to the diameter of the round edge. Unlike the real fogging systems, water was ejected from a Ø1mm hole located at the mid-span of the blade’s L.E., as shown in Fig. 4(a) and 4(b) respectively. The purpose of ejecting water from these simplified holes geometries is to understand the influence of the size and geometry of the nozzles in the real GT systems. This simplified water ejection method also helped in understanding the influence of the T.E. of the blade as well as allowed us to visualize the droplets kinematic downstream of the T.E. with ease.

2.3 Flow Conditions

Experiments were performed at four different air flow conditions. The maximum air velocity which can be achieved in the present experimental setup was 40 m/sec. Though the air flow velocity is relatively very small compared to that of the real machines, however, the Reynolds number based on the chord length of the blade corresponds to that of the real machines (i.e., of an order of 10^5), since fogging technique is more efficient for small to medium scale turbines. Table 3 summarizes the experimental flow conditions under which experiments are performed. The air flow velocity is categorized into three groups, namely High Air Velocity (or High Air Momentum) Case, Medium Air Velocity (or Momentum) Case and Low Air Velocity (or Momentum) Case. In the present study, the blades were kept at 0-degree Angle of Attack (AOA) and the room temperature water was used, whose mass flow rate was controlled by changing the height of the water column in the tank and is expressed mathematically by a dimensionless

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reynolds number (Re_a)</th>
</tr>
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<tbody>
<tr>
<td>Case</td>
<td>High air velocity</td>
<td>Case A: 40</td>
</tr>
<tr>
<td></td>
<td>Medium air velocity</td>
<td>Case B: 30</td>
</tr>
<tr>
<td></td>
<td>Low air velocity</td>
<td>Case C: 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Case D: 20</td>
</tr>
<tr>
<td>Ambient temperature [K]</td>
<td>298.5 (approx.)</td>
<td></td>
</tr>
<tr>
<td>Water temperature [K]</td>
<td>Room temperature water</td>
<td></td>
</tr>
<tr>
<td>Dimensionless mass flow rate (MFR)</td>
<td>2 ~ 32</td>
<td></td>
</tr>
<tr>
<td>Air density [kg/m^3]</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>Water density [kg/m^3]</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Angle of attack [degree]</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Experimental flow conditions
\[ MFR = \frac{\dot{m}_l}{\mu_l C} \]  

(1)

3. Image Processing Method

Shadowgraph images were taken using a high-speed camera (Photron FASTCAM APX-RS) by placing a diffuser plate between the high-speed camera and the light sources, as shown in Fig. 3. The lights (Photron HVC-UL) used have a power output of 250W each. A 105 mm NIKON lens was used along with an extension ring to visualize the characteristics of droplets formation after the T.E. of the cascade blade. The frame size of captured images was 1024 sq. pixels having a field of view of about 80mm x 80mm. The corresponding shutter rate and the frame rate was 1/30,000 sec and 1000 frames per sec (fps) respectively.

The captured images were grey scale having a pixel intensity ranging from 0 to 255, as shown in Fig. 5 (a). These images were difficult to analyse and were converted into the corresponding binary images using an in-house image processing code, Fig. 5 (b), by subtracting a dry scale image with that of the two-phase image, Fig. 5 (a). It should be noted that in this study, droplets having an area less than the 5 sq. pixels are neglected to avoid the noise which might had caused during the binarization process. It is assumed that the droplets are perfectly spherical whose diameter is given by that of the circle.

\[ D = \sqrt{\frac{4A}{\pi}} \]  

(2)

Table 4 – Weber number based on the blade thickness

| Parameter | Blade profile | | | |
|---|---|---|---|
| | Air velocity [m/sec] | Flat | Elliptical |
| T.E. thickness [mm] | 6 | 2.25 |
| Weber no. based on T.E. thickness (\(We_a\)) | 40 | 160 | 60 |
| (approx.) | 30 | 90 | 34 |

Fig. 5 Image processing technique (conversion from grey scale image to binary image)

Fig. 6 Schematic of droplets formations from the T.E. of the blade
4. Theoretical Model Formulation and Droplet Size Measurement

4.1 Mathematical Model Formulation for the role of T.E. thickness in droplet formations

One of the most important parameters which define the characteristics of ligament and droplets size distribution is the profile thickness of the T.E.. Though, in the present study, the profile geometry of the two blades are completely different which resulted in different flow velocity distribution after the T.E. of the blade. For the purpose of simplicity and comparison, it is assumed that both blades configuration are equivalent in profile but only have different T.E. thickness. By this assumption, the effect of T.E. thickness on the characteristics of ligament and droplets size distribution after the T.E. region can be easily compared by using a non-dimensional parameter. Such assumption is considered to be appropriate as the liquid film usually accumulates at the T.E. and starts to form droplets (or ligaments) from over there, as discussed by Javed et al. (2016).

Table 4 categorizes the Weber number based on the thickness of the blades which is mathematically given by Eq. (3)

\[
We_a = \frac{\rho_a U_a^2 t}{\sigma}
\]  

(3)

It is also assumed that the water film is accumulated at the T.E. in the form of a circular cylinder, and the droplets are formed directly from this cylinder, as shown schematically in Fig. 6. For more details, the readers are referred to our previous study as given in Javed et al. (2016).

Based on the law of conservation of mass (see Fig. 6),

\[
\text{mass}_{\text{span}} \approx \text{mass}_{\text{prim}}
\]  

(4)

\[
\frac{\pi}{4} D_{\text{span}}^2 \lambda_{\text{span}} \approx \frac{\pi}{6} D_{\text{prim}}^3
\]  

(5)

According to Lefebvre (1989),

\[
D_{\text{span}} \approx \frac{\lambda_{\text{span}}}{4.51}
\]  

(6)

Substituting Eq. (6) in Eq. (5),

\[
\lambda_{\text{span}} \approx 13.6 D_{\text{prim}}
\]  

(7)

The wavelength of accumulated water has a direct influence on the resulting primary droplet diameter formation, as represented by the Eq. 7. For the ligament(s) to atomize without an aid of any external forces, the energy can be approximated by,

\[
E_{\text{span}} \approx \sigma \Delta A \approx \sigma (4A_{\text{prim}} - A_{\text{span}})
\]  

(8)

\[
E_{\text{span}} \approx \frac{m_1 \sigma}{\rho_l} \left( \frac{4}{D_{\text{prim}}} - \frac{4}{\lambda_{\text{span}}} \right)
\]  

(9)

Substituting Eq. (7) in Eq. (9),

\[
E_{\text{span}} \approx \frac{m_1 \sigma}{\rho_l} \left( \frac{3.7}{D_{\text{prim}}} \right)
\]  

(10)

Similarly, the energy required from the gaseous phase to atomize the droplets from the T.E. of the blade can be approximated by the K.E. of air and is mathematically expressed as

\[
E_a = \frac{1}{2} m_a U_a^2
\]  

(11)

Based on the energy conservation principle, it can be approximated that

\[
E_{\text{span}} = k \cdot E_a
\]  

(12)

here, \( k \) is the proportionality constant whose value can be obtained from the experiments

\[
\frac{m_1 \sigma}{\rho_l} \left( \frac{3.7}{D_{\text{prim}}} \right) = k \cdot \frac{1}{2} m_a U_a^2
\]  

(13)

By rearranging Eq. (13),

\[
D_{\text{prim}} = \frac{7.4}{k} \frac{m_1 \sigma}{m_a \rho_l U_a^2}
\]  

(14)

\[
D_{\text{prim}} = \frac{7.4}{k (ALR) We_t}
\]  

(15)

where, \( ALR \) is the air to liquid ratio and \( We_t \) is the Weber number based on the thickness of the T.E.
\[ ALR = \frac{m_a}{m_l} \]
\[ We_t = \frac{\rho_l U^2 a}{\sigma} \]

From Eq. (15), if the Weber number (based on the T.E. thickness) remains the same then the thicker the blade’s T.E. is, larger would be the size of the primary droplets produced and vice versa. Also, the primary droplets formed is inversely proportional to the square of the air velocity, resulting in smaller droplets size at high air flow velocity and vice versa. It should be noted that in Eq. (15), the Weber number at the T.E. was obtained based on the air velocity only and not on the basis of velocity difference of the accumulated water and the surrounding airflow. This is due to the fact that the velocity of the accumulated water in the form of the circular cylinder is almost zero at the T.E. of the blade when compared with the main flow air velocity. Also, from Eq. 10, in case of no external forces (i.e. surrounding air), the liquid possessing greater surface tension would remain attached at the T.E. and vice versa.

### 4.2 Droplet Size Measurement

One of the most important parameter for the atomization process is the accumulated water at the T.E. of the blade. Droplets size distribution after the T.E. of the blade were measured at 0.25-, 0.5-, 0.75-, and 1-chord length (C) distance from the tip of the T.E.. The measuring frame was chosen to be 0.1C and 1C in width and height, as shown in Fig. 7. Such sub-framing technique is advantageose as by doing this the repeatability of the droplets can be avoided in the analysis. Binary images were generated in a similar way as shown in Fig. 5 (b). In the field of atomization, it is common to represent the spray system diameter in terms of the representative diameter, which is given by

\[ D_{ab} = \left( \frac{\sum N_i D_{i}^{-1}}{\sum N_i D_{i}^{-1}} \right)^{1-b} \] (16)

Many droplet sizes are used to characterize the droplets size distribution; however, the most commonly used droplet sizes are Sauter Mean Diameter (SMD or D32) and the Average Diameter (D10). The D32 droplet is defined as the diameter of a drop having the same volume to surface area ratio as the entire spray, whereas the D10 represents the average droplet of the entire spray system.

### 5. Results and Discussions

Figure 8 and 9 show the droplets size distribution after the elliptical and flat profile blades respectively. In both figures, the filled and unfilled symbols represent the D10 and D32 droplet size distribution respectively. Black, red, blue and purple colours represent the droplets size distribution measured at 0.25-, 0.5-, 0.75-, and 1-C positions, Fig. 7.
whereas, the dotted lines represent the mean value at these positions. From Fig. 8 and 9, the droplets size distribution at a particular position remained identical due to the similar effect of aerodynamic and surface tension forces. For high air momentum case, a large deviation of droplets size is observed near the T.E., which is due to the large deformation of droplets caused by high momentum forces. Another reason for this deviation is the presence of few droplets which remained attached to the side walls of the test section. Though in the in-house image processing code maximum number of side wall droplets were removed, there remained few droplets which might have caused such large deviation in the droplet size distribution near the T.E.. On the other hand, for low momentum cases, the deviation is not significant due to the dominant effect of liquid’s surface tension forces over the aerodynamic forces, Fig. 8 and 9.

Figure 10 (a) and 10 (b) show the primary droplet size distribution measured near the T.E. of the elliptical and flat profile blade respectively. In Fig. 10, the black, red, blue and purple colours correspond to the Case A, B, C and D respectively. Similarly, the dotted lines correspond to the mean droplet size. Figure 10 shows that the droplet size distributions remain nearly identical, which is primarily due to the fact that once the droplets detached from the ligaments, their size is independent of the injected water flow rate. The size of these droplets is then determined by two forces; namely the aerodynamic force, which is due to the surrounding air velocity, and the surface tension force of the liquid. As both quantities remained unchanged, the droplet size distribution for a particular case also remained

**Figure 8** Average (D10-left) and Sauter Mean Droplet (D32-right) diameter distribution after the T.E. of the elliptical blade (Left: Case A – $M \approx 192$, Right: Case D – $M \approx 40$)

**Figure 9** Average (D10) and Sauter Mean Droplet (D32) diameter distribution after the T.E. of the flat blade (Left: Case A – $M \approx 192$, Right: Case D – $M \approx 40$)
unchanged.

In order to predict the size of the primary droplets size formed, the authors use the theoretical model based on energy conservation as given in detail by Javed et al. (2016)

\[ D_{\text{prim}} \approx \frac{k \cdot A_F}{2} + \frac{1}{\lambda_{\text{span}}} \]  \hspace{1cm} (17)

where, \( k \) is proportionality constant which can be determined from experiment and the factor \( A_F \) is given by,

\[ A_F = \frac{4.91 \rho_l}{\sigma} \cdot \left[ \frac{400}{\pi} \right]^{\frac{1}{3}} \cdot [m_l]^{-\frac{2}{3}} \cdot [C]^2 \cdot [\rho_a]^2 \cdot [U_a]^6 \cdot [Re]^{-\frac{2}{3}} \]

Figure 11(a) and 11(b) shows the experimentally measured droplets against the theoretically predicted expression,

![Graphs showing primary droplet size distribution](image)

Fig. 10 Primary droplet size distribution after the T.E. of the blade

![Graphs showing primary droplet size distribution](image)

Fig. 11 Prediction of primary droplets size distribution after the T.E. of the blade
Eq. (17), for the elliptical and flat profile blades respectively. The theoretical model gives a reasonable estimation of predicting the primary droplets after the T.E. of the blades. The deviation of experimental results from the theoretical results is thought to be mainly due to the consideration of coarse droplets only and neglecting the smaller droplets as explained by Javed et al. (2016). From the comparison of theoretical and experimental data, a maximum deviation for the elliptical and the flat profile blade case was found to be under 15% and 10% respectively.

Figure 12 compares the experimental results of primary droplets size distribution obtained for the elliptical and flat profiles blade respectively, against the Weber number based on the T.E., as given by Eq. (15). As predicted, the primary droplets produced from the thicker T.E. (i.e., flat blade) is larger in size compared to the thinner T.E. profile (i.e., elliptical blade), which agrees with the theoretically derived Eq. (15). At low Weber number ($We_t$) the droplets size increases, which is due to the fact that at low Weber number cases the breakup of droplets from the T.E. is dominated due to the influence of the strong surface tension forces of the liquid over the surrounding aerodynamic forces and vice versa.

The disintegration of droplets from the T.E. of the blade is not merely the breakup of ligament and droplets formation but also the distribution of these disintegrated droplets into the surrounding gaseous medium after the T.E. of the blade. Depending on the air momentum the shedded droplets formed from the T.E. of the blade, the droplets can spread in either a wide- or narrow-angle. A wider droplets distribution region not only affect the surrounding air momentum but also causes damages to the incoming rotor blades by the bombardment of droplets over a large area onto the rotor blades. To estimate the droplets distribution angle after the T.E. region of the cascade blade, intensity
Images were generated by adding 1000 grey scale images. These images were then converted into the corresponding RGB image, Fig. 13(a), and were further modified by reducing the threshold intensity level to the 70% of the original image, Fig. 13(a), to obtain the corresponding threshold intensity image, Fig. 13(b). From Fig. 13(b), near the T.E. a red region was observed, which represents the high-water accumulation region whereas away from the T.E. a blue region (low (water) intensity region) corresponds to the distribution of the shedded (or disintegrated) droplets. The blue region in Fig. 13(b) is separated from the surrounding black region (containing no water) making it simpler to approximate the droplets distribution angle. Though, in fact, there is a major difficulty in defining the droplets distribution angle as the droplets boundary became slightly curved as the distance from the T.E. increases. To overcome this difficulty the droplets distribution angle is defined by the two straight lines (white lines), as shown in Fig. 13(b). The angle suspended between the two thresholds lines is then used to approximate the droplets shedding angle, as shown in Fig. 13(b).

Figure 14 and 15 show the effect of air velocity on the droplets distribution angle for the Case A and D respectively. For high air momentum case, the droplets distribution angle for the flat blade, Fig. 14(b), is marginally smaller compared to that of the elliptical blade, Fig. 14(a). On the other hand, in case of low air momentum ratio, the droplets shedding angle for the flat blade was larger than that of the elliptical blade, as shown in Fig. 15. In order to understand this phenomenon, the Stokes number of the droplets was calculated as expressed mathematically by Crowe et al. (2011) at different positions downstream of the blade.

\[
St \approx \frac{\rho_l D^2 U_a}{18 \mu_a C}
\] (18)

From Fig. 16(a), at high air momentum the Stokes number of the droplets for the flat blade is marginally less than that of the elliptical blade resulting the droplets to continue to flow along with the main air flow. In other words, as the Stokes number for the elliptical blade is marginally larger, it results in larger droplets distribution angle, Fig. 14(a).
Also, based on the mathematical expression given by Eq. (15), as the primary droplets size formed for the high momentum air cases are smaller, allowing the droplets to move along the air path, leading to a small droplets distribution angle. As the air velocity was reduced, the corresponding distribution angle for the flat blade became larger than that of the elliptical blade, as shown in Fig. 15. Comparing this with Fig. 16(b), the corresponding Stokes number of the flat blade is also found to be greater than that of the elliptical and thus resulted in the formation of relatively coarse droplets which did not follow the air path. Due to their larger size, these droplets do not flow along the air path as they possess high momentum, and thus leads to the larger distribution angle. It is due to this reason that at low air momentum case, the droplets formed for flat blade are relatively larger than that of the elliptical profile, and resulted in larger droplets distribution angle aft the T.E. of the flat blade, as shown in Fig. 15. In future studies, the authors would like to compare the above phenomena for the same profile blades, with different T.E. thickness only.

6. Summary and Conclusions

In this study, comparisons of droplets size formation after the T.E. of the elliptical and flat profile blades were discussed. For the purpose of comparison and simplicity, it was assumed that the profile geometry did not have any significant role in droplets size distribution after the T.E. of the blade. It should be kept in mind that in this study, the effect of vortex shedding phenomenon is not considered. Based on these assumptions, a theoretical model was proposed to compare the role of the thickness of the T.E. on the primary droplets formation aft the T.E. of the blade. From this study, following conclusions can be made:

- Droplets size distribution after the T.E. remain identical for all the cases, from 0.25- to 1-C positions.
- The primary droplets formed after the T.E. of the blade is inversely proportional to the square of the air velocity.
- If the Weber number of the different blade profiles is kept the same, then the blade with greater T.E. thickness would result in larger droplets and vice versa.
- The droplets distribution angle is determined by the Stoke’s number. For high air momentum case, the droplets distribution angle formed after the T.E. is smaller and otherwise, i.e.,

\[
\theta \propto \frac{1}{U_a}
\]

Nomenclature

<table>
<thead>
<tr>
<th>Latin Symbols</th>
<th>Greek Symbols</th>
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<tbody>
<tr>
<td>( C ) chord length of the blade, m</td>
<td>( \rho ) density, kg/m³</td>
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</tbody>
</table>
$$D \quad \text{diameter, m}$$

$$U \quad \text{velocity, m/sec}$$

$$t \quad \text{thickness of the T.E. of the blade, m}$$

$$m \quad \text{mass flow rate, kg/sec}$$

$$E \quad \text{energy, J}$$

$$A \quad \text{area, m}^2$$

$$A_f \quad \text{factor A}$$

$$\mu \quad \text{dynamic viscosity, N.sec/m}^2$$

$$\sigma \quad \text{coefficient of surface tension, N/m}$$

$$\theta \quad \text{angle, degree}$$

$$\lambda \quad \text{wavelength, m}$$

Subscripts

- $l$ liquid
- $a$ air
- $prim$ primary droplet
- $span$ span wise
- 10 average diameter
- 32 Sauter Mean Diameter (SMD)

Dimensionless Numbers

- $Re_a \quad \text{Reynolds Number of air } (\rho_a U_a C / \mu_a)$
- $MFR \quad \text{Dimensionless mass flow rate } (m_l / \mu_l C)$
- $M \quad \text{Momentum ratio } (\rho_a U_a^2 / \rho_l U_l^2)$
- $We_a \quad \text{Weber number (based on T.E. thickness) } (\rho_a U_a^2 t / \sigma)$
- $We_t \quad \text{Weber number (based on T.E. thickness) } (\rho_t U_t^2 t / \sigma)$
- $ALR \quad \text{air to liquid ratio } (m_a / m_l)$
- $St \quad \text{Stokes number } (\rho D^2 U_a / 18 \mu_a C)$

References


Bhargava, and Meher-Homji, C., B., Parametric Analysis of Existing Gas Turbines with Inlet Evaporative and Overspray Fogging, ASME Turbo Expo (2002), Amsterdam, The Netherlands


