Experimental Investigation of Characteristics of Liquid Behaviour around a Cascade Blade

Baber Javed¹, Toshinori Watanabe², Takehiro Himeno² and Seiji Uzawa²

¹ School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN

²Department of Aeronautics & Astronautics, The University of Tokyo

ABSTRACT

Fogging has been gaining considerable importance among the gas turbine manufacturer mainly because of being the most cost-effective and efficient method to augment the power output of gas turbines. In this paper, the fundamental experimental study was conducted to understand the characteristics of two-phase phenomena around the cascade blade. Water was ingested from the holes located at different spanwise positions at the blade's leading edge. Detailed visualization was conducted by taking shadowgraph images using a high-speed camera. Characteristics of water film formation and the droplet size distribution were measured and were also theoretically investigated. It was found that the liquid film thickness and the droplet size aft the trailing edge of the cascade blade were mainly functions of the surface tension of the liquid and the surrounding air velocity, whereas, it was independent of the shape and size of water ingestion hole.

NOMENCLATURE

Latin Symbols

A	area, m ²
C	chord Length of the blade, m
D	diameter, m
h	height, m
V	velocity, m/sec
$\dot{Q}$	volume flow rate, m ³ /sec
t	thickness of the T.E. of the blade, m
w	width, m
g	acceleration due to gravity, m/sec ²
k	dimensional wave number, m
$\dot{m}$	mass flow rate, kg/sec
H	height of the test section, m
p	pressure, Pa
$\vec{u}$	velocity vector, m/sec
x, y	x- and y-axis direction
c_f	coefficient of friction

Greek Symbols

ρ	density, kg/m ³
μ	dynamic viscosity, N.sec/m ²
ν	kinematic viscosity, m ² /sec
γ/σ	coefficient of surface tension, N/m
λ	wavelength, m
α	dimensionless wave number
$\sum$	complex tangential perturbation term
Π	complex normal perturbation term

Subscripts

l	liquid
a	air
10	mean diameter
32	sauter mean diameter (SMD)

Dimensionless Numbers

Re_a	Reynolds Number of air ($\rho_a V_a C / \mu_a$)
R	Reynolds Number of liquid ($\rho_l V_l h_l / \mu_l$)
T	Inverse Weber Number ($\gamma / \rho_l h_l V_l^2$)
G	Inverse Froude Number ($g h_l / V_l^2$)
MFR	Dimensionless mass flow rate ($\dot{m}_l / \mu_l C$)
M	Momentum ratio ($\rho_a V_a^2 / \rho_l V_l^2$)
We_a	Weber no. (based on T.E. thickness) ($\rho_a V_a^2 t / \sigma$)

INTRODUCTION

The global energy demand has been increasing since the start of this century especially in the emerging markets. World's electricity demands are mainly fulfilled by the thermal power plants, and more commonly coal and gas are used as fuel. The demand of cost-effective and environmentally friendly thermal energy devices are increasing to minimize the fuel consumption as well as to minimize the emission of harmful gases in the viewpoint of global environment. Among the thermal power systems, gas turbines (GT) systems are considered as one of the most important devices. It is well known that the efficiency of GT decreases with increasing temperature of the incoming air. According to Chaker et al. [1], a rise of 1°C causes an energy output loss of about 0.54-0.9%. Bhargava et al. [2] concluded that the power output of GT could drop as much as 15 to 20% at an ambient atmospheric temperature of 35°C. One approach to overcome the loss of GT power output during hot seasons is to cool the inlet air. The cooled dense air provides high mass flow rates, resulting in an increase in GT power output. Fogging

Fig. 1 Fogging in inlet plenum of AHAT systems

is considered to be one of the simplest and effective power augmentation methods for cooling the inlet air. In the fogging, fine droplets of demineralized water are sprayed into the inlet plenum of the GT from a rack of nozzles, as shown in Fig. 1. Based on the water ingestion point, the principle can be classified as inlet fogging and over-fogging as shown schematically in Fig. 1(a) and 1(b) respectively. Gotoh et al. [4] had proposed Advanced Humid Air Turbine (AHAT) systems, which worked on the fogging principles and are expected to achieve higher efficiency without increasing the combustion temperature or pressure. AHAT systems are economically cheap as the cost of installing AHAT plant is less than that of the combined cycle plants since the AHAT systems require no steam turbines and other high-pressure equipment, such as HRSG, etc. [5]. Potential benefits of water ingestion from the thermodynamic point of view have been identified by many researchers ([6-8]) etc. and it was generally concluded that the

Fig. 3 Experimental layout

Fig. 2 Schematics of water droplets around cascade

water ingestion increases the overall thermal efficiency of the GT systems.

Despite the extensive thermodynamic study about the two-phase phenomena in GT systems, the fundamentals of the kinematics of two-phase flow have not been understood in detail. Therefore, the main aim of the present experimental study is to understand the characteristics of the liquid film formation on the blade's surface and to determine the droplet size distribution aft the trailing edge (T.E.) of the cascade blade.

Figure 2 shows a schematic image of droplet behaviour in a cascade. Water droplets from nozzles impinge on the leading edge (L.E.) of the compressor blades. Droplets impact on a surface is often accompanied by the breakup of larger droplets into smaller ones due to droplet deformation and splashing. The water in which these droplets are contained can either be ejected back into the airflow or moved as a thin film of water on the blade surface. The water film flows towards the T.E. due to the aerodynamic forces and forms globules at the T.E.. These globules remain attached to the T.E. because of the surface tension and grow in the direction of the airflow and along the T.E.. As the size of globules increases, the aerodynamic force acting to tear the droplet away from the T.E. also increases. And when the increasing aerodynamic force exceeds the adhesive force of surface tension, which is holding the globules at the T.E., the globules will separate from the T.E. in the form of droplets and flow into the aft T.E. region of the blade.

EXPERIMENTAL SETUP

For the experiment, an open-type wind tunnel was used. The present setup has the following features;

- Ease of adjusting angle of attack (AOA) of the aerofoil,
- To have a better optical accessibility, and
- Ease of modification to the test facility.

Figure 3 shows the experimental layout used in the study. A centrifugal blower drives the air into the test section. A settling chamber is placed between the test section and the blower, which removes the turbulence from the air passage and straighten the incoming flow. A test blade at 0-degree AOA is mounted inside the test section. A droplet stopper and collector setup was fixed at the end of the test section to prevent the droplets to splash and spread in the downstream region. The cross section of the test section is 80 x 100 mm². In order to have an ease of visualizing the two-phase phenomenon, the side walls of the test blades were made from the acrylic material.

Water Supply Mechanism

Water was supplied to the test blade via a water column having a diameter of 150 mm, as shown in Fig. 4. At the bottom of the water column, a hand valve was equipped to control the

Table 1 Specification of flat blade

Parameter	Value
Aerofoil type	Flat (with round edges)
Material	Brass
Chord length (C)	50 mm
Span length (S)	80 mm
Maximum thickness	6 mm
Thickness ratio	12 %
Hole diameter (for injecting water)	5 mm
T.E. thickness (t)	6 mm

Table 2 Water ingestion holes at L.E. specifications

Geometrical Shape	Size
Small Hole (S.H.)	$\phi 1$ mm
Medium Hole (M.H.)	$\phi 1.2$ mm
Large Hole (L.H.)	$\phi 1.5$ mm
Slit	1 mm x 3 mm

flow rate of water to the test blade.

Test Blade

In order to obtain the fundamental knowledge of the two-phase phenomenon, geometrically simple blade profile was adopted in the experiment, namely, flat plate blade with rounded L.E. and T.E., as shown schematically in Fig. 5. Table 1 shows specifications of the blade. In the real systems, the effect of droplets size formed by utilizing different nozzles types and the corresponding ejected diameter had been studied recently by Chaker et al. [9]. However, the effects of different nozzles types and the ejected water droplets effects from the T.E. has not been studied. Therefore, different profile ingestion holes at the L.E. were used to grasp the influence of size and geometry of the nozzles in the real GT systems. These geometries were assumed to cause the similar effect by forming a thin film as by the different nozzle types having different diameters. By this assumption, our understanding of the effect of nozzle types on two-phase characteristics can be understood in a better way, especially the droplets formed from the T.E., as they are the main source of coarse droplets in real systems. Figure 6 shows the location and geometry of the four types of ingestion holes made on the L.E.. Table 2 gives the specifications of the ingestion holes. The S.H. geometry was located at the mid-span of the blade, whereas, M.H. and L.H. geometries were present at 0.1-S from the mid-span (Fig. 6). The slit geometry was made at 0.1-S from the L.H., i.e., 0.2-S from the mid-chord.

Experimental Conditions

Table 3 summarizes the experimental flow conditions under

Table 3 Experimental conditions

Parameter		Value	
Name	Case	V_a (m/sec)	Re_a
High Air Velocity	Case A	40	1.35×10^5
Medium Air Velocity	Case B	30	1.01×10^5
Low Air Velocity	Case C	20	0.67×10^5
Dimensionless mass flow rate (MFR)		2 ~ 32	
Water temperature		Room water temperature	
Ambient air temperature (K)		298 (approx.)	
Angle of attack (degree)		0

Fig. 4 Water supply mechanism **Fig. 5 Test blade (Flat profile blade)** **Fig. 6 Position & shape of ejection holes at L.E.**

which experiments were performed. Though the velocity was very slow compared with that of the real machines, the Reynolds number based on the chord length of the blade is nearly in the same order of the real machines, that is, the order of 10^5 [5]. In the present study, air flow velocity was categorized into the three groups, namely High-, Medium- and Low Air Velocity Case, which corresponds to the air velocity of 40, 30 and 20 m/sec respectively.

Measurement Method

Figure 3 shows the setup of the experimental layout. A high-speed camera (Photron FASTCAM APX-RS) was used to capture high-speed images. The field of view of these images was 80 mm x 80 mm approximately. For acquisition rate of 1,000 frames per seconds (fps), the shutter speed was chosen as 1/15000 seconds, which was sufficient to visualize the individual droplets. Background illumination was provided by two high-intensity light source, each having a 250W power. A

(a) Grey scale image (Intensity varies from 0 to 255)

(b) Binary image (Intensity – 0 and 255 only)

Fig. 7 Image processing technique (Conversion of grey scale image to binary image)

diffuser plate was placed between the high-speed camera and the light source to diffuse the light uniformly. An in-house code was developed to detect the liquid particles from the shadowgraph images. This shadowgraph image, shown in Fig. 7 (a) were first subtracted from the dry images (i.e., containing no water) and were then converted to the binary images, Fig. 7 (b), by using a canny edge detection method as discussed briefly in [10]. The droplets area was calculated from the binary image and it was further assumed that the droplets were spherical in nature having diameter given by

$$D = \sqrt{\frac{4A}{\pi}} \quad (1)$$

Film width was experimentally measured by taking the high-speed images at the mid-chord of the blade on the upper

side (or suction side (S.S.)) of the blade with about 190 square pixels equivalent to 10 mm². The fps and shutter speeds were

Fig. 8 Oil flow visualization (Case A - $V_a = 40$ m/sec)

Fig. 9 Velocity distribution aft the T.E. of blade

(a) Case A (Air velocity 40 m/sec)

i. Diameter 1 mm

ii. Slit

(b) Case C (Air velocity 20 m/sec)

Fig. 10 Water film visualization

Fig. 11 Theoretical liquid film profile

1000fps and 1/15000 seconds respectively. To estimate the velocity of the thin liquid film, water containing the tracer particles was used. The tracer particle motion was experimentally detected by measuring the distance of the particles movement in two consecutive images. Since the tracer particles size of the micrometer order, therefore, it was assumed that they flow with the same velocity as that of the water film. Similarly, the same images were utilized to measure the wave length of the waves.

RESULTS AND DISCUSSIONS

Surface Oil Flow Visualization

Surface oil flow visualization was conducted in which a mixture of oil and titanium dioxide was used. This mixture was painted as a thin layer on the blade and the blade was put inside the wind tunnel. Figure 8 shows the oil traces on the S.S. of the blade for Case A at 0-degree AOA. Flow separation took place just near the L.E. of the blade. At the T.E. of the blade, a thin line of oil was observed, which accumulated due to the separation. Overall, however, the flow is seen to be almost two-dimensional in nature.

Velocity Distribution aft the T.E. of the blade:

Figure 9 shows the velocity distribution measured at 0.25- and 1-C distance aft the T.E. of the flat profile blade measured at the mid-span position. In all the cases, the velocity distribution aft the blade remains nearly symmetrical because of the same S.S. and lower surface (or pressure side (P.S.)) profile shape. Additionally, the velocity deficit was found to be maximum near the T.E., which diminishes gradually as the distance aft the T.E. increases

Visualization of Water Film Flow on the Blade Surface

Fig. 12 Water film thickness

The visualized images in Fig. 10 show the occurrence of the following three basic phenomena;

1. Liquid film formation on the blade surface,
2. Liquid accumulation at the T.E., and
3. The breakup of ligaments and droplets formation aft the T.E. region of the blade.

In the present paper the two-phase phenomena behaviour is classified into two parts; namely;

- Characteristics of liquid film, and
- Characteristics of water droplets formation aft the T.E. of the blade.

Both characteristics were studied separately.

CHARACTERISTICS OF LIQUID FILM

Classification of liquid film pattern

Based on the flow visualization, the water film patterns is categorized into the following two main categories;

i. Wavy Pattern: Figure 10 (a) shows the wavy film structure formed for the S.H. and Slit ejection hole geometries at high air momentum (Case A). The appearance of the wave structure formed on the S.S. of the blade was found to be almost similar due to the same aerodynamic forces and was independent of the geometry of ingestion holes. The wave showed a complex structure mainly due to the flow separation at the L.E. of the blade. The film showed abrupt widening at the L.E. due to the separation, making a large surface area exposed to the free stream air, and resulted in a more complex wavy pattern. From the visualization results, these waves had relatively high wave velocity and were smaller in wavelength due to the influence of the aerodynamic forces. This results in widened width and thus the film thickness formed on the blade's surface was also small.

ii. Smooth Pattern: When the air momentum was small (Case C), as shown in Fig. 10 (b), the water film pattern showed a mirror-like smooth structure. From the high-speed images, it was observed that the smoothness of the water film structure was almost independent of the ingestion hole geometry and was governed by the surface tension forces and the surrounding aerodynamic forces. Similarly, the smoothness of the film was not affected by the flow rate of water. The water film moves much slower than that with the wavy pattern as the liquid's surface tension property is significant to resist the external forces (i.e., the aerodynamic forces).

Fig. 13 Physical mechanism of Craik's model

In short, the wave pattern is mainly dependent upon the force balance between the aerodynamic and the surface tension forces of the liquid. Greater the aerodynamic forces are the wavier will be the liquid film pattern formed and vice versa.

Liquid Film Thickness

In this study, a theoretical model is proposed to investigate the thickness of the liquid film. Figure 11 shows a schematic image of the liquid film profile at the mid-chord of the flat blade profile. Referring to Fig. 11, the steady flow of the liquid film can be governed by the Navier-Stokes equation

$$\nabla \cdot \vec{u} = 0 \quad (2)$$

$$(\vec{u} \cdot \nabla) \vec{u} = -\frac{\nabla p}{\rho_l} + \nu (\nabla^2 \vec{u}) \quad (3)$$

The liquid film moves only in the main air flow direction (x-direction) whose height varies in the y-direction, as shown schematically in Fig. 11. For such thin liquid films, the external forces is given by the shear stresses applied by the aerodynamic forces and the volume flow rate of the liquid film can be written as

$$\dot{Q} = w_l \int_0^{h_l} u(y) dy \quad (4)$$

Assuming, linear velocity profile and solving for $u(y)$ by using Eq. (3), the theoretical expression for the liquid film thickness can be given by

$$h_l = 2 \sqrt{\frac{\dot{Q} \mu_l}{c_f \rho_a w_l V_a^2}} \quad (5)$$

From Eq. (5), the liquid film thickness decreases with an increase in air velocity and a decrease in the liquid's flow rate. Similarly, greater the viscosity of the liquid is, thicker is the liquid film formed and vice versa. In this study, liquid film width was measured experimentally from the high-speed images and the liquid film thickness was calculated using Eq. (5). Figure 12(a), 12(b) and 12(c) shows a liquid film thickness measured at the mid-chord of the flat blade profile using Eq. (5) for the Case A, B and C respectively. Though, in Fig. 12 small discrepancies of experimental data are observed especially Fig. 12(c), which might be due to the fact that the aerodynamic forces might be marginally different due to the different ingestion holes positions. However, this needs to be further evaluated in the future by using laser sensors. From the Eq. (5) the liquid film thickness is only dependent on the liquid and gaseous state properties and is completely independent of the ingestion hole geometry. Monnier et al. [12] considered the stretching of the liquid film by using the minimum energy concept. Based on the minimum energy principle, the shape and motion of the liquid film become stable under the condition at which the total energy gained by the liquid from the air become minimum.

Water Film Instability (Craik's Model) [13]

Due to the non-availability of the sensors, in the present study, the instability of water film was studied based on Craik's model [13]. Craik obtained Orr-Sommerfeld equation by solving the Navier-Stokes equation. According to the model, the instability is defined by the dimensionless amplification factor for the thin liquid films is theoretically estimated as given by Eq. (6).

$$\alpha c_l R = \frac{(\alpha R)^2}{3} \left\{ \Pi_r + \frac{3\Sigma_i}{2\alpha} - T\alpha^2 - G \right\} \quad (6)$$

From Eq. (6), greater the surface tension of the liquid is more stable it will be and vice versa. Also, the limiting criterion of the above equation is given by the instability term, i.e., the term in the parenthesis. In Eq. (6), Π_r and Σ_i represents the normal and shear pressure perturbation respectively, which are generated due to the aerodynamic forces. The terms T and G are the dimensionless representation of surface tension and flow inertia terms possessed due to the liquid properties.

The physical phenomena of Craik's model can be easily understood by Fig. 13. If a thin liquid film has enough restoring forces (the surface tension and inertia), it opposes the aerodynamic forces and results in a smooth liquid's surface, as shown in Fig. 13 (a). On the other hand, if the aerodynamic forces exceed the liquid's surface tension force, an instability pattern appears on the liquid surface on the surface of the blade, Fig. 13 (b) and 13 (c). Due to the aerodynamic force, a normal force is applied on the surface of the liquid, which results in the appearance of an instability pattern at the liquid's surface. The normal stress (Π_r) applies an upward force on the crest and a downward force on the trough, resulting in displacing the liquid away from the troughs and towards the crests. The shear stresses (Σ_i) due to the aerodynamic force accelerates the fluid in the

Table 4 – Dimensionless wave number

MFR	6.75	10.0
Ingestion Hole Size	Dimensionless wave number (α)	
	Case A	Case B
Diameter 1-mm	0.37±0.012	0.59±0.009
Diameter 1.2-mm	0.57±0.02	0.61±0.01
Diameter 1.5-mm	0.36±0.017	0.67±0.018
Slit	0.45±0.013	0.61±0.02

Fig. 14 Water film stability criteria

windward direction and deaccelerate the fluid in the leeward direction (i.e., in the direction opposite to the aerodynamic force). This process results in the acceleration of the liquid crest's and vice versa. According to the authors, the role of gravity term (G) is considered to play a role of stabilizing and de-stabilizing the liquid film, depending upon the blade's surface. On the S.S. of the blade, it plays a role of stabilizing the liquid film structure by applying a downward force (i.e., towards the blade's surface), as shown in Fig. 13 (b) and is also discussed by Craik [13]. However, according to the author's opinion, the gravity term (G) on the P.S. of the blade destabilize the liquid film by exerting a downward force on the liquid film, resulting in the film structure to move away from the blade's surface, as shown schematically in Fig. 13 (c). However, Fig. 13(c), this will be investigated in future as based on the current experimental setup, high speed images of the lower side (i.e., P.S.) cannot be taken. Table 4 shows the values of dimensionless wavelength based on the experimental results measured on the S.S. of the blade from the high speed camera. Similarly, Fig. 14 shows that whenever the wave number exceeds the critical value

of α the instability on the film surface will occur. i.e., the liquid flow becomes unstable. From Fig. 14, for the same value of wave's wavelength, Case A shows the maximum energy transferred compared to the Case B. Due to large aerodynamic forces, such instability pattern of liquid film is also termed as K-H instability (Fig. 10 (a)), which leads to the atomization due to the R-T instability [14].

CHARACTERISTICS OF DROPLETS FORMATION

Classification of Ligament Breakup

From the analysis of high-speed images the accumulated water at the T.E. of the blade was governed by the Weber number (based on T.E. thickness) and the momentum ratio, given by Eq. (7) and (8) respectively.

$$We_a = \frac{\rho_a V_a^2 t}{\sigma} \quad (7)$$

$$M = \frac{\rho_a V_a^2}{\rho_l V_l^2} \quad (8)$$

The breakup of ligament was mainly due to the dominant effects of the following forces;

i. Breakup of ligaments due to Aerodynamic forces: At high air momentum (Case A) having $M \approx 192$, $We_a \approx 160$ the surface waves on the blade surface play a major role in the breakup of droplets from the T.E. [14], as shown in Fig. 15 (a). When the surface wave reaches at the T.E., it accumulates there to a certain amount. The vortex sheds from the T.E. causes the destabilization of the accumulated water. This results in the chunk of large amount of water to start shedding from the T.E., forming large amount of droplets aft the T.E.. It was generally observed that due to relatively large density of the liquid, the water accumulates towards the lower end of the T.E. (due to gravity effect and higher liquid density) and the droplets shedding mostly starts from the lower end of the blade's T.E.. The accumulated water moves upward, i.e., towards the S.S. The vortex shed from the opposite side, i.e., S.S. further enhanced this phenomenon by stripping a large number of droplets from the accumulated water and also started to move the accumulated water downwards. This process kept on

Fig. 15 Breakup of ligaments at the T.E. of cascade blade (Ø 1 mm)

continuing until enough amount of water in the form of droplets was shed aft the T.E. region. From the visualization of the high speed images, the droplets formed were smaller in size due to the vibrational mode of a breakup [15], having low momentum and followed the air path. In vibration breakup, the surrounding gaseous flow field interact with droplet in such a way as to increase the amplitude of oscillation of droplet, which ultimately leads to the breakup of droplet. The secondary droplets produced are nearly half in size and the number of droplets are comparatively very few compare to the other modes of breakup.

ii. Breakup of ligaments due to Surface tension forces: For $M \approx 48$ and $We_a \approx 40$ (Case C) a completely different breakup phenomenon occurred, as shown in Fig. 15 (c). Due to the dominance of surface tension forces, the water accumulates at the T.E. remains attached for long time resulting in the large amount of water accumulation at the T.E.. The accumulated water was always seen to be oscillating upward and downward due to the vortex shedding from the T.E.. Due to weak aerodynamic forces in this case, the shed vortex did not

contribute to the stripping of droplets from the accumulated

Fig. 16 Droplets size measurement positions

Fig. 17 Droplet size distribution aft the T.E. region for $\varnothing$ 1 mm ingestion hole geometry

Fig. 18 Droplet size distribution aft the T.E. region for slit ingestion hole geometry

Fig. 19 Summary of D10 droplet size distribution

Fig. 20 Summary of D32 droplet size distribution

water at T.E., instead elongated the accumulated water in the wind-ward direction (Fig. 15 (c)). When this accumulated water reached its critical amount then the vortex shedding (mostly from the lower end of the blade's T.E.) resulted in the formation of large and even multiple bags of the ligaments, whose length occasionally exceeded up to 0.5-C. The bag formation was followed by the generation of a large number of droplets. Some of the large droplets were seen to further underwent bag mode of a breakup [15]. In bag mode, a droplet get flatten and is blown out into a hollow bag attached to a circular rim. On disintegration the bag produces numerous fine droplets, whereas rim contains large proportion of original drop (around 70% by mass [16]). Since the droplets produced in this case were mainly coarse, the droplets had relatively high momentum compared with Case A, and, therefore, generally did not follow the air flow path.

For intermediate air momentum (Case B), Fig. 15 (b), an intermediate breakup phenomena occurred, signifying the importance of both the aerodynamic and surface tension forces.

Droplets Size Distribution aft the T.E.

The droplet size was measured aft the T.E. of the blade at 0.25-, 0.5-, 0.75- and 1-C downstream from the tip of the T.E.. The size of measurement window width was chosen to be 0.1-C and its height as 1-C, as shown in Fig. 16. According to Lefebvre [16], the representation diameter is given by

$$D_{ab} = \left(\frac{\sum N_i D_i^a}{\sum N_i D_i^b} \right)^{\frac{1}{(a-b)}} \quad (9)$$

In the field of atomization, several representative diameters are used to define the fineness of the droplets. Among those, the commonly used are the Mean (D10) and Sauter Mean (D32) droplets size. Figure 17 shows the results of the case with $\phi 1\text{mm}$ ingestion hole geometry at different amount of water ingestion (MFR) and air momentum. The filled ($\bullet$) and unfilled labels ($\circ$) represents the D10 and D32 diameters respectively. Considering Fig. 17 (a), the droplet size is almost identical at the measured four positions for every MFR. This is mainly because the droplet size is primarily governed by the T.E. profile and the air momentum. Since the velocity of accumulated water at the T.E. is nearly zero, the accumulated water at the T.E. experiences uniform aerodynamic forces under different MFR. This leads to the identical slip velocity for the droplet and surrounding air, generating the identical droplet size at each position aft the T.E.. Figure 18 represents the measured droplets for slit geometry for varying MFR and at different air momentum cases. Like $\phi 1\text{mm}$, the slit profile also shows an identical trend, i.e., for a selective air momentum the droplets size remains the same at a particular position for varying MFR. It should also be noted that near the T.E., i.e., at the 0.25-C position the droplets deviation is large compared to the other positions mainly due to the large deformation of droplets as well as the presence of the ligaments

(Fig. 15). The slit which is positioned near the test section wall (Fig. 6), causing the droplets to easily get deposited at the side wall of the wind tunnel, resulting in a large deviation in the droplet sizes (Fig. 18 (a) and 18 (b)). A similar tendency of droplet size distribution was observed for the $\varnothing$ 1.2 mm and $\varnothing$ 1.5 mm hole geometries. Figure 19 and 20 shows the summarized D10 and D32 droplet size distribution for all the ingestion hole geometries. The droplet size remains the same for the same air momentum and T.E. profile configuration and is independent of the ingestion hole geometries. It can be seen from the Fig. 19 and 20 that the primary droplets size produced for high air momentum (Case A) are relatively smaller in diameter than that of the low air momentum (Case C). The droplet size decreases marginally for high momentum case (Case A, Fig. 19 (a) and 20 (a)) as the distance aft the T.E. increases mainly due to the vibrational breakup of droplets. This results in an overall minor change in the gradient of droplets size with increasing aft T.E. distance. On the other side, the droplet size near the T.E. for low air momentum case (Case C, Fig. 19 (c) and 20 (c)) is relatively coarse and the size decreases abruptly as the distance aft the T.E. increases, because of the bag mode of the breakup of these coarse droplets. Due to the bag breakup, the gradient of droplets size change for Case C was large.

Summing up, in the case of high momentum and weber number case (Case A) the location of droplet size breakup occurs near to the T.E. due to the large aerodynamic forces resulting in the small amplitude of ligament oscillation. On the other hand, for low momentum and weber number case (Case C), the droplets underwent breakup further downstream of the T.E. due to their high amplitude of oscillation.

SUMMARY AND CONCLUSIONS

A detailed experimental investigation was conducted to understand the characteristics of the liquid film and the droplet size distribution aft the T.E. of the cascade blade in humid air. The present study is expected to provide a better understanding of the droplet laden flow in turbomachines and provide a basis for the CFD calculations as well. It is reminded that in this study the above two characteristics were studied separately. The conclusions drawn from this study are summarized as follows;

- Water film thickness is a function of the blade profile, mass flow rate of water, liquid's viscosity and the air velocity, and is almost independent of the size of the ingesting hole. An increase in air velocity, a decrease in the mass flow rate and surface tension causes a decrease in the film thickness.
- Aerodynamic forces destabilize the liquid film structure, whereas, the liquid property of surface tension stabilizes it.
- For the same T.E. profile, the primary droplet size decreases with an increase in the air momentum.
- The droplet size distribution aft the T.E. region does not change if the slip velocity between the droplets and the surrounding air remains the same.
- The primary droplets formed in the case of the high momentum are smaller in size compared to that of the low momentum case.

REFERENCES

[1] Chaker, M., A., Meher-Homji, Cyrus, B., and Mee, Thomas, "Inlet Fogging of Gas Turbine Engines-Part I: Fog Droplet Thermodynamics, Heat Transfer and Practical Considerations", *ASME Journal of Engineering Gas Turbines & Power*, 2004, 126 (3), 545-558

[2] Bhargava, R., K., Meher-Homji, C., B., Chaker, M., A.,

Bianchi, M., Melino, F., Peretto, A., and Ingistov, S., "Gas Turbine Fogging Technology: A State-of-the-Art Review—Part I: Inlet Evaporative Fogging- Analytical and Experimental Aspects", *Journal of Engineering Gas Turbines & Power*, 2006, GT2005-68336

[3] Yagi, M., Araki, H., Tagawa, H., Koganezawa, T., Myoren, C., and Takeda, T., "Progress of the 40 MW-Class Advanced Humid Air Turbine Tests", *Journal of Engineering Gas Turbines & Power*, 2013, Vol. 135, 112002

[4] Gotoh, J., Sato, K., Araki, H., and Marushima, S., "Efficient and Flexible AHAT Gas Turbine System", *Hitachi Review*, 2011, Vol. 60 (7)

[5] Araki, H., Koganezawa, T., Myouren, C., Higuchi, S., Takahashi, T., and Eta, T., "Experimental and Analytical Study on the Operation Characteristics of the AHAT System", *Journal of Engineering Gas Turbines & Power*, 2012, Vol. 134, 051701-1

[6] M. Bianchi, "Gas turbine power augmentation technologies: A systematic comparative evaluation approach," *ASME Turbo Expo 2010*, 2010, GT2010-22948

[7] Eisfeld, T., and Joos, F., "On the thermodynamic modelling of two-phase flow compression with dispersed water droplets in air", *ISROMAC 14*, 2012, Paper-227, Honolulu, US

[8] Zheng, Q., Sun, Y., Li, S., and Wang, Y., "Thermodynamic analyses of wet compression process in the compressor of gas turbine," *Proceedings of ASME Turbo Expo 2002*, 2002, GT2002-30590

[9] Chaker, M., Meher-Homji, C., B., Mee III, T., "Inlet fogging of Gas Turbine Engines – Part B: Fog droplet sizing analysis, nozzle types, measurement and testing", *Proceedings of ASME Turbo Expo, 2002*, 2002-GT-30563

[10] https://en.wikipedia.org/wiki/Canny_edge_detector (accessed date: Jan 2015)

[11] Javed, B., Watanabe, T., Himeno, T., and Uzawa, S., "Characteristics of Liquid Sheet Disintegration from the Trailing Edge of the Cascade Blade", *Asian Joint Conference on Propulsion and Power*, 2016, AJCPP2016-135

[12] Monnier, H., Mhiri, N and Falk, L., "Falling liquid film stability in microgas / liquid absorption", *Chemical Engineering & Processing*, 2010, Vol. 49 (9), pp. 953-957

[13] Craik, A., D., "Wind-generated Waves in Thin Films", *Journal of Fluid Mechanics*, 1966, Vol. 26, part 2

[14] Boukra, M., Cartellier, A., Ducasse, E., Gajan, P., Lalo, M., Noel, T., and Strzelecki, A., "Use of Faraday instabilities to enhance fuel pulverisation in air-blast atomisers", *Comptes Rendus Mécanique - Combustion for aerospace propulsion*, 2009, Vol. 337 (6–7), pp. 492-503

[15] Crowe, C., Sommerfield, M., Tsuji, Y. "Multiphase Flows with Droplets and Particles-Second Edition, 2011, CRC Press

[16] Lefebvre, A., H., "Atomization and Sprays" *Combustion: An International Series*, 1989, Taylor & Francis