Effects of mainstream velocity and setting position on flow separation control of a curved wall using plasma actuators

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Abstract
Dielectric barrier discharge (DBD) plasma actuators were used for the active control of flow separation on a curved wall simulated suction surface of a gas turbine blade at three different mainstream velocities, \( U_{MS} = 2.2 \) m/s, 4.1 m/s, and 6.3 m/s. Owing to the change in mainstream velocity, the Reynolds number was varied as \( Re = 1.7 \times 10^4, 3.1 \times 10^4, \) and \( 4.7 \times 10^4 \), respectively. Particle image velocimetry system was used to obtain two-dimensional velocity field measurements. The amplitude of input voltage for the plasma actuator was changed from \( \pm 2.0 \) kV to \( \pm 4.0 \) kV. At the lower mainstream velocity, \( U_{MS} = 2.2 \) m/s (\( Re = 1.7 \times 10^4 \)), the separated flow induced on a curved wall was considerably reduced by the flow control using the DBD plasma actuator. Moreover, the effect of flow control by the plasma actuator was gradually reduced at the higher mainstream velocities, \( U_{MS} = 4.1 \) m/s and 6.3 m/s (\( Re = 3.1 \times 10^4 \) and \( 4.7 \times 10^4 \), respectively). The flow control effect was improved by changing the position of the plasma actuator. When the plasma actuator was positioned immediately before the separation point, it exhibited better flow control effects than when positioned immediately behind the separation point.

Keywords: Turbine, Separation, Plasma actuator, Active flow control, Particle image velocimetry (PIV), Low Reynolds number

1. Introduction

A low-pressure turbine blade of small and medium-sized gas turbines for aircraft propulsion experiences low Reynolds numbers below \( 2.5 \times 10^4 \) at high altitudes, where the air density is low (Sondergaard et al., 2002). At these low Reynolds numbers, the boundary layer is dominated by laminar flow and is susceptible to flow separation, which develops into increased loss, leading to reduced performance. Several researches focusing on the aerodynamics of turbine blades at low Reynolds numbers have been published (Howell et al., 2001; Volino and Hultgren, 2001).

Different passive and active flow control techniques have been developed to increase the efficiency of a turbine blade at low Reynolds numbers (Rivir et al., 2004). Passive flow control devices, such as fixed turbulators and dimples, are traditional approaches to trigger transition and induce re-attachment, but create undesirable drag at high Reynolds number. Active flow control devices can be employed only when required. Vortex generating jets and plasma actuators are prominent subjects of recent research in active flow control.

The application of a dielectric barrier discharge (DBD) plasma actuator was demonstrated by Roth et al. (1998) and this actuator has been developed over the last decade through fundamental studies of discharge and employed in a wide range of applications, such as cylinder, bluff body, wing and turbine (Corke et al., 2010).

Figure 1 shows a simple schematic configuration of a DBD plasma actuator. The DBD plasma actuator consists of a dielectric layer sandwiched between exposed (top) and encapsulated (bottom) electrodes. Applying high voltages (approximately \( 5 \) kV\( _{pp} \) – \( 40 \) kV\( _{pp} \)) at radio frequencies (approximately 1 kHz – 50 kHz) between the exposed and encapsulated electrodes forms a layer of glow discharge plasma across the dielectric surface. This induces a tangential air jet with a horizontal velocity component. It is known that the direction of the resultant tangential jet is constant and
independent of changes in the polarity of the applied voltage.

DBD plasma actuators have also been used in numerous low-pressure turbine separation control studies (Rizzetta and Visbal, 2007; Suzen et al., 2007; Wall et al., 2007; Burman et al., 2011; Marks et al., 2011). However, these studies were limited to two-dimensional stationary linear turbine cascades. As there have been few studies on three-dimensional annular turbine cascades, the authors of the present paper are planning to apply DBD plasma actuators in their annular turbine wind tunnel with a single-stage axial-flow turbine (Matsunuma, 2006, 2007).

The objective of this study is to investigate the most effective active flow control operation of DBD plasma actuators via simplified experiments using a curved wall with velocity distributions around a turbine rotor. The experimental results in this study will be used as the fundamental data for considering the application of a DBD plasma actuator for an annular turbine wind tunnel. In the previous study by the current authors, the effects of input voltage were examined (Matsunuma and Segawa, 2012). The shape of the curved wall and the previous experimental data were also used for the verification of computational fluid dynamic (CFD) studies by other research groups (Bell et al., 2015; Martinez et al., 2017). This paper presents the results of particle image velocimetry (PIV) measurement to understand the flow separation control by plasma actuators at three different mainstream velocities, $U_{MS} = 2.2$ m/s, 4.1 m/s, and 6.3 m/s and two different setting position of the plasma actuators, $x = 16.0$ mm, and 30.6 mm.

2. Experimental facility and method

Figure 2 shows the measurement system. The wind tunnel is a low-speed, open-circuit, blower-type facility with a test section of dimensions $305$ mm $\times$ $85$ mm $\times$ $65$ mm.

A curved wall plate (streamwise length $L = 100$ mm) was installed in the test section of the wind tunnel in order to simulate the separated flow on the suction surface of a turbine blade. Figure 3 shows the geometry and near-surface

**Fig. 2** Measurement system **Fig. 3** Corresponding turbine blade
velocity distribution at the midspan of the corresponding turbine blade. Various measurements were obtained around the blade, such as 5-hole pressure probes, hot-wire anemometry and laser Doppler velocimetry, in the annular turbine wind tunnel in previous studies (Matsunuma, 2006, 2007). The curved wall represents the velocity and pressure distributions of the suction surface of the corresponding turbine blade (Matsunuma and Segawa, 2012). The shape of the curved wall was designed using a simple one-dimensional continuity argument to match the design surface velocity and pressure distributions. Although actual turbine blades have both suction and pressure surfaces, the only suction surface with flow separation was considered in this research.

PIV was employed to quantify the behavior of the flow field around the curved wall. The laser was a 25-mJ/pulse, double-pulse Nd-YAG laser (MiniLase II, 20Hz, New Wave Research Co. Ltd.). Atomized dioctyl sebacate oil with a mean particle diameter of 1 µm was injected upstream of the test section via a pressurized oil chamber. Image pairs were captured using a camera (PIV CAM 13-8, TSI Inc.) of resolution 1,280 × 1,024. TSI software was used to calculate the velocity vectors from the peak correlation of groups of particles between frames, using conventional cross-correlation algorithms on a 32 × 32 pixel grid. In order to calculate the averaged velocity distributions, 50 instantaneous velocity distributions were measured at each experimental condition in this study. Time-averaged distributions were calculated by averaging 50 instantaneous velocity distributions. Turbulence intensity was calculated as follows:

\[ \text{Tu} = \left( \frac{u_x'^2 + u_y'^2}{2} \right) / U_{MS}. \] (1)

The turbulence intensity was normalized by the mainstream velocity near the trailing edge at \( x = 100 \text{ mm} \), \( U_{MS} \).

Figure 4 shows the geometry of the measurement section and the PIV grids. Plasma actuators were mounted near the flow separation point at the front of the adverse pressure gradient region (deceleration region) on the curved wall. The edge of the top electrode of the plasma actuator, where the surface plasma is formed, was located at \( x = 30.6 \text{ mm} \) from the leading edge (position A) and \( x = 16.0 \text{ mm} \) from the leading edge (position B), as shown in Fig. 4. In this study, the effects of the positions of the plasma actuator were investigated. In Fig. 4, the plasma actuator position A is located immediately behind the flow separation point, and the plasma actuator position B is located immediately before the flow separation point. In previous study, regarding the plasma actuator position of active flow control of a NACA0012 airfoil, Tsubakino et al.,2007, found that the leading edge (separation point) is most effective.

In these experiments, the rotating speed of a blower of the wind tunnel was selected at three different conditions (100 rpm, 200 rpm, and 300 rpm) in order to change the mainstream velocity. Reynolds number was also varied with the change in the mainstream velocity. The mainstream velocity near the trailing edge (\( x = 100 \text{ mm} \)) was almost constant, \( U_{MS} = 2.2 \text{ m/s} \) for the lower Reynolds number, \( U_{MS} = 4.1 \text{ m/s} \) for the medium Reynolds number, and \( U_{MS} = 6.3 \text{ m/s} \) for the higher Reynolds number, as shown in Figs. 12, 14, and 16. Therefore, the Reynolds numbers based on the streamwise length of the curved wall, \( L \), and the mainstream velocity near the trailing edge, \( U_{MS} \), were \( Re = 1.7 \times 10^4 \), \( Re = 3.1 \times 10^4 \), and \( Re = 4.7 \times 10^4 \) respectively, for the mainstream velocities \( U_{MS} = 2.2 \text{ m/s} \), \( 4.1 \text{ m/s} \), and \( 6.3 \text{ m/s} \).

Figure 5 shows a photograph of the plasma actuator used in this study. A thin sheet of polyimide (thickness 125 µm, relative permittivity \( \varepsilon' \approx 3 \)) was used as the dielectric barrier. As the electrodes, thin sheets of copper (thickness = 35
µm) were glued and pressed onto both sides of the dielectric. A high-voltage, high-frequency power supply (PG1040F, PSI Inc.) that can output bipolar sinusoidal waveforms was used to supply input signals to the top and bottom electrodes. The encapsulated bottom electrode was connected to ground, \( V_g = 0 \) V. The amplitude of input voltage to the top electrode \( V_{AC} \) was varied from ±2.0 kV to ±2.8 kV (4.0–5.6 kVp-p). The frequency of input voltage \( f_p \) was fixed at \( f_p = 8.1 \) kHz.

3. Results and discussion
3.1 Distributions of time-averaged velocity and turbulence intensity (plasma actuator: position A)
3.1.1 Lower mainstream velocity, \( U_{MS} = 2.2 \) m/s (lower Reynolds number, \( Re = 1.7 \times 10^4 \))

Figure 6 shows the time-averaged velocity distributions at various input voltages (baseline, \( V_{AC} = \pm 2.0 \) kV, and \( \pm 2.8 \) kV) at the lower mainstream velocity, \( U_{MS} = 2.2 \) m/s (Reynolds number, \( Re = 1.7 \times 10^4 \)). The large separation region observed in the baseline (actuator off) condition in Fig. 6(a) is gradually reduced by the effect of active control.

![Flow](image1)
![Flow](image2)
![Flow](image3)

Fig. 6 Time-averaged velocity distributions at various DBD-PA input voltages (PA: position A) \( (U_{MS} = 2.2 \) m/s, \( Re = 1.7 \times 10^4 \))

![Flow](image4)
![Flow](image5)

Fig. 7 Turbulence intensity distributions at various DBD-PA input voltages (PA: position A) \( (U_{MS} = 2.2 \) m/s, \( Re = 1.7 \times 10^4 \))
in Figs. 6(b), (c). In this figure, streamlines were also superimposed upon the velocity contours. In the baseline condition in Fig. 6(a), a large reverse flow is observed in the separation region. In the flow control case of $V_{AC} = \pm 2.0$ kV in Fig. 6(b), large recirculation exists in the separation region (the center is located at $x = 80$ mm), and the low-velocity region is slightly reduced near the trailing edge. In the flow control case of $V_{AC} = \pm 2.8$ kV in Fig. 6(c), the recirculation disappears and the separation region becomes considerably smaller. The separated flow attaches at $x = 80$ mm.

Figure 7 shows the turbulence intensity distributions at various input voltages at the lower mainstream velocity, $U_{MS} = 2.2$ m/s. In this figure, velocity vectors were also superimposed upon the turbulence intensity contours. In the baseline condition in Fig. 7(a), a high turbulence intensity region exists at the boundary line between the main flow and separated flow. A wide high turbulence intensity region is suddenly generated after $x = 70$ mm. This phenomenon occurs because the separated boundary layer is stable from $x = 20$ mm to $x = 70$ mm and becomes unstable after $x = 70$ mm, which is observed in the instantaneous velocity distributions. In the flow control case of $V_{AC} = \pm 2.0$ kV in Fig. 7(b), the high turbulence intensity region is generated after $x = 50$ mm, which is further upstream than the baseline condition. In Fig. 7(c), as the input voltage is increased, the high turbulence intensity region moves further upstream and closer to the curved wall and becomes smaller in width.

### 3.1.2 Medium mainstream velocity, $U_{MS} = 4.1$ m/s (medium Reynolds number, $Re = 3.1 \times 10^4$)

Figure 8 shows the time-averaged velocity distributions at various input voltages (baseline, $V_{AC} = \pm 2.0$ kV, $\pm 2.8$ kV, and $\pm 4.0$ kV) at the medium mainstream velocity, $U_{MS} = 4.1$ m/s (Reynolds number, $Re = 3.1 \times 10^4$). The large separation region observed in the baseline condition in Fig. 8(a) is slightly reduced compared with that at the low mainstream velocity condition, $U_{MS} = 2.2$ m/s in Fig. 6(a). Although the large separation region is gradually reduced by the effect of active control in Figs. 8(b)–(d), the flow control effect is smaller than that at the low mainstream velocity shown in Figs. 6(b)–(d). In the baseline condition in Fig. 8(a), large recirculation is observed in the separation region and its center is located at $x = 70$ mm. In the flow control case of $V_{AC} = \pm 2.0$ kV in Fig. 8(b), the size of the separation region is almost the same. On the contrary, in the flow control case of $V_{AC} = \pm 2.8$ kV in Fig. 8(c), the velocity near the plasma actuator region increases, the recirculation in the separation region is reduced in size, and the position of its center moves further upstream at $x = 55$ mm. In the flow control case of $V_{AC} = \pm 4.0$ kV in Fig. 8(d), the recirculation in the separation region become smaller and moves further upstream.

Figure 9 shows the turbulence intensity distributions at various input voltages at the medium mainstream velocity, $U_{MS} = 4.1$ m/s. In the baseline condition in Fig. 9(a), the high turbulence intensity region becomes wide after $x = 60$ mm, which is further upstream compared with the baseline condition at low mainstream velocity, $U_{MS} = 2.2$ m/s, in Fig. 7(a). This is because the separated boundary layer becomes unstable and transitional owing to the increased Reynolds number according to the increased mainstream velocity. In the flow control conditions in Figs. 9(b)–(d), as the input voltage is increased, the high turbulence intensity region moves further upstream and closer to the curved wall. However, the change is smaller than that in the lower mainstream velocity condition shown in Figs. 7(b)–(d).

### 3.1.3 Higher mainstream velocity, $U_{MS} = 6.3$ m/s (higher Reynolds number, $Re = 4.7 \times 10^4$)

Figure 10 shows the time-averaged velocity distributions at various input voltages (baseline, $V_{AC} = \pm 2.0$ kV, $\pm 2.8$ kV, and $\pm 4.0$ kV) at the higher mainstream velocity, $U_{MS} = 6.3$ m/s (Reynolds number, $Re = 4.7 \times 10^4$). The separation region observed in the baseline condition in Fig. 10(a) is further reduced compared with those at the lower mainstream velocity condition in Figs. 6(a) and 8(a). This is due to the increased Reynolds number according to the increased mainstream velocity. The center of recirculation is located at $x = 50$ mm. In the flow control case in Figs. 10(b)–(d), the velocity near the plasma actuator increases, the recirculation in the separation region is reduced in size, and the position of its center moves further upstream at $x = 40$ mm.

Figure 11 shows the turbulence intensity distributions at various input voltages at the higher mainstream velocity, $U_{MS} = 6.3$ m/s. In the baseline condition in Fig. 11(a), the high turbulence intensity region becomes wide immediately after the separation point. This is because the separated boundary layer becomes transitional to the turbulence boundary layer owing to the increased Reynolds number according to the increased mainstream velocity. In the flow control conditions in Figs. 11(b), (c), the high turbulence intensity region has no change. In Fig. 11(d), the high turbulence intensity region moves closer to the curved wall, but the change is smaller than those in the lower mainstream velocity conditions shown in Figs. 7 and 9.
Fig. 8 Time-averaged velocity distributions at various DBD-PA input voltages (PA: position A) 
($U_{MS} = 4.1$ m/s, $Re = 3.1 \times 10^4$) 

(a) Baseline 
(b) Flow control ($V_{AC} = \pm 2.0$ kV) 
(c) Flow control ($V_{AC} = \pm 2.8$ kV) 
(d) Flow control ($V_{AC} = \pm 4.0$ kV) 

Fig. 9 Turbulence intensity distributions at various DBD-PA input voltages (PA: position A) 
($U_{MS} = 4.1$ m/s, $Re = 3.1 \times 10^4$) 

(a) Baseline 
(b) Flow control ($V_{AC} = \pm 2.0$ kV) 
(c) Flow control ($V_{AC} = \pm 2.8$ kV) 
(d) Flow control ($V_{AC} = \pm 4.0$ kV)
Time-averaged velocity distributions at various DBD-PA input voltages (PA: position A) ($U_{MS} = 6.3 \text{ m/s}, \ Re = 4.7 \times 10^4$)

Turbulence intensity distributions at various DBD-PA input voltages (PA: position A) ($U_{MS} = 6.3 \text{ m/s}, \ Re = 4.7 \times 10^4$)
3.2 Distributions of time-averaged streamwise velocity component and turbulence intensity near trailing edge (plasma actuator: position A)

3.2.1 Lower mainstream velocity, $U_{MS} = 2.2$ m/s (lower Reynolds number, $Re = 1.7 \times 10^4$)

Figures 12 and 13 show the distribution of the time-averaged streamwise velocity component and turbulence intensity near the trailing edge, $x = 100$ mm, at the lower mainstream velocity, $U_{MS} = 2.2$ m/s. The bottom of the vertical axis (vertical position $y = 25$ mm) corresponds to the surface of the curved wall at the trailing edge.

In Fig. 12, the mainstream velocity is almost constant ($U_{MS} = 2.2$ m/s) for all input voltage conditions. In the baseline conditions (black line in the figure), a large velocity deficit with reverse flow exists near the surface of the curved wall. The boundary layer thickness (distance between the curved wall surface and vertical position with 99% of the main flow velocity) is approximately 22 mm (from $x = 25$ mm to $x = 47$ mm). At $V_{AC} = \pm 2.0$ kV (red line), the reverse flow is reduced but the boundary layer thickness is the same as the baseline. At $V_{AC} = \pm 2.8$ kV (orange), the velocity in the boundary layer is considerably increased. The reverse flow region completely disappears and the boundary layer thickness is reduced to 14 mm. The shape of the velocity distributions in the boundary layer becomes convex.

In Fig. 13, the maximum turbulence intensity in the boundary layer is 17.7% in the baseline condition. The maximum turbulence intensity increases to 20% at $V_{AC} = \pm 2.0$ kV, and decreases to 14% at $V_{AC} = \pm 2.8$ kV. As the input voltage is increased, the vertical position of the maximum turbulence intensity moves close to the curved wall and the width of the high turbulence intensity region decreases.

3.2.2 Medium mainstream velocity, $U_{MS} = 4.1$ m/s (medium Reynolds number, $Re = 3.1 \times 10^4$)

Figures 14 and 15 show the distribution of the time-averaged streamwise velocity component and turbulence intensity near the trailing edge at the medium mainstream velocity, $U_{MS} = 4.1$ m/s.

The mainstream velocity in Fig. 14 is also almost constant ($U_{MS} = 4.1$ m/s) for all input voltage conditions. In the baseline conditions (black line in the figure), a velocity deficit with reverse flow exists near the surface of the curved wall, but the deficit width of the reverse flow is smaller than that at the lower mainstream velocity, $U_{MS} = 2.2$ m/s, in Fig. 12. The boundary layer thickness is approximately 22 mm, which is the same as that at the lower mainstream velocity. At $V_{AC} = \pm 2.0$ kV (red), the velocity distribution is almost the same as the baseline (no improvement). At $V_{AC} = \pm 2.8$ kV (orange), the reverse flow region completely disappears, and the boundary layer thickness is reduced to 19 mm. At $V_{AC} = \pm 4.0$ kV (blue), the velocity in the boundary layer is increased and the boundary layer thickness is reduced to
In Fig. 15, the maximum turbulence intensity in the boundary layer is 18.5% in the baseline condition. The maximum turbulence intensity increases to 20% at $V_{AC} = \pm 2.0 \text{ kV}$, and decreases to 18% at $V_{AC} = \pm 4.0 \text{ kV}$. As the input voltage is increased, the vertical position of the maximum turbulence intensity moves close to the curved wall and the width of the high turbulence intensity region decreases.

### 3.2.3 Higher mainstream velocity, $U_{MS} = 6.3 \text{ m/s}$ (higher Reynolds number, $Re = 4.7 \times 10^4$)

Figures 16 and 17 show the distribution of the time-averaged streamwise velocity component and turbulence intensity near the trailing edge at the middle mainstream velocity, $U_{MS} = 6.3 \text{ m/s}$. 

**Fig. 14** Streamwise velocity distributions near trailing edge (PA: position A) ($U_{MS} = 4.1 \text{ m/s, } Re = 3.1 \times 10^4$)

**Fig. 15** Turbulence intensity distributions near trailing edge (PA: position A) ($U_{MS} = 4.1 \text{ m/s, } Re = 3.1 \times 10^4$)

**Fig. 16** Streamwise velocity distributions near trailing edge (PA: position A) ($U_{MS} = 6.3 \text{ m/s, } Re = 4.7 \times 10^4$)

**Fig. 17** Turbulence intensity distributions near trailing edge (PA: position A) ($U_{MS} = 6.3 \text{ m/s, } Re = 4.7 \times 10^4$)
In Fig. 16, the mainstream velocity is also almost constant \((U_{MS}=6.3 \text{ m/s})\) for all input voltage conditions. In the baseline conditions (black line in the figure), the reverse flow region observed in the lower mainstream velocity conditions in Figs. 12 and 14 disappears near the surface of the curved wall. The boundary layer thickness is approximately 22 mm. As the input voltage is increased, the velocity in the boundary layer is slightly increased.

In Fig. 17, the maximum turbulence intensity in the boundary layer is 18.5% in the baseline condition. The maximum turbulence intensity decreases gradually to 12.5% at \(V_{AC}=\pm 4.0 \text{ kV}\).

### 3.3 Effects of mainstream velocity on boundary layer parameters (plasma actuator: position A)

#### 3.3.1 Boundary layer displacement thickness and momentum thickness at trailing edge

Figure 18 shows the displacement thickness, \(\delta_1\), of the boundary layer near the trailing edge at the three mainstream velocities. At the lower mainstream velocity, \(U_{MS}=2.2 \text{ m/s}\) (green line), the displacement thickness is drastically reduced by as much as 77% at \(\pm 2.8 \text{ kV}\). At the medium mainstream velocity, \(U_{MS}=4.1 \text{ m/s}\) (blue line), the displacement thickness is reduced by 41% at \(\pm 4.0 \text{ kV}\). At the higher mainstream velocity, \(U_{MS}=6.3 \text{ m/s}\) (purple line), the displacement thickness is reduced by 26% at \(\pm 4.0 \text{ kV}\).

Figure 19 shows the momentum thickness, \(\delta_2\), of the boundary layer near the trailing edge at the three mainstream velocities. At the lower mainstream velocity, \(U_{MS}=2.2 \text{ m/s}\) (green line), the momentum thickness is reduced by 20% at \(\pm 2.8 \text{ kV}\). At the medium mainstream velocity, \(U_{MS}=4.1 \text{ m/s}\) (blue line), and the higher mainstream velocity, \(U_{MS}=6.3 \text{ m/s}\) (purple line), the momentum thickness is reduced by only 7% at \(\pm 4.0 \text{ kV}\).

#### 3.3.2 Boundary layer shape factor at trailing edge

Figure 20 shows the boundary layer shape factor \(H_{12}(=\delta_1/\delta_2)\) near the trailing edge at the three mainstream velocities.

An empirical single-variable correlation using \(H_{12}\) was developed for incipient and full detachment and for reattachment of turbulent boundary layers on two-dimensional surfaces (Kline et al., 1983). The \(H_{12}\) criteria of the correlation are \(H_{12} \geq 4.0\) for the separated region (full detachment), \(2.2 \leq H_{12} \leq 4.0\) for intermittent detachment, and \(H_{12} \leq 2.2\) for the attached boundary layer (reattachment).

At the lower mainstream velocity, \(U_{MS}=2.2 \text{ m/s}\), the shape factor \(H_{12}\) is 6.41 at the baseline condition and is reduced to 1.85 at \(V_{AC}=\pm 2.8 \text{ kV}\), as the amplitude of input voltage increases. From the correlation described above, the boundary layer at baseline is separated, and that at \(V_{AC}=\pm 2.8 \text{ kV}\) is reattached.

At the medium mainstream velocity, \(U_{MS}=4.1 \text{ m/s}\) (blue line), the shape factor \(H_{12}\) is 5.18 at the baseline condition
and is reduced to 3.2 at $V_{AC} = \pm 4.0$ kV. From the correlation, the boundary layer at baseline is separated, and that at $V_{AC} = \pm 4.0$ kV is intermittently detached.

At the higher mainstream velocity, $UMS = 6.3$ m/s (purple line), the shape factor $H_{12}$ is 3.5 at the baseline condition and is reduced to 2.8 at $V_{AC} = \pm 4.0$ kV. From the correlation, the boundary layer at both baseline and $V_{AC} = \pm 4.0$ kV is intermittently detached.

### 3.3.3 Total pressure loss estimation

Figure 21 shows the estimated total pressure loss. The total pressure loss coefficient, $CP_t$, was calculated from the boundary layer displacement thickness, $\delta_1$, and momentum thickness, $\delta_2$, using the following correlation of an idealized control volume model for a trailing edge (Denton, 1993):

$$ CP_t = \left( \frac{\delta_1 + t}{w} \right)^2 + \frac{2\delta_2}{w} - \frac{C_{pb} t}{w} $$

where $w$ is the passage width (60 mm), $t$ is the thickness of the trailing edge of the original blade (1.9 mm), and $C_{pb}$ is the base pressure coefficient. As the value of $C_{pb}$ is unknown in this study, the typical value of $C_{pb} = -0.15$ is used for this estimation. The third term including $C_{pb}$ is approximately 3–5% of $CP_t$; therefore, the effect of unknown $C_{pb}$ value is considered to be relatively smaller than that of the first and second terms.

At the lower mainstream velocity, $UMS = 2.2$ m/s (green line), the total pressure loss coefficient is 0.172 at the baseline condition. The total pressure loss is reduced to 0.078 (55% reduction) at $\pm 2.8$ kV.

At the medium mainstream velocity, $UMS = 4.1$ m/s (blue line), the total pressure loss coefficient is 0.174 at the baseline condition. The total pressure loss is slightly increased to 0.183 (5% rise) at $\pm 2.0$ kV. Further, the total pressure loss is reduced to 0.134 (23% reduction) at $\pm 2.8$ kV, and to 0.122 (30% reduction) at $\pm 4.0$ kV.

At the higher mainstream velocity, $UMS = 6.3$ m/s (purple line), the total pressure loss coefficient at the baseline condition is reduced to 0.157. The total pressure loss is gradually reduced to 0.146 (7% reduction) at $\pm 2.8$ kV, and to 0.131 (16% reduction) at $\pm 4.0$ kV.

At the higher mainstream velocity, the effect of flow control by the plasma actuator is reduced compared with that at the lower mainstream velocity. Therefore, the installation of the plasma actuator system requires improvement (e.g., increased input voltage, change of the plasma actuator location) for higher mainstream velocity flows.
Fig. 22 Time-averaged velocity distributions at various DBD-PA input voltages (PA: position B) ($U_{MS}=6.3 \text{ m/s, } Re=4.7 \times 10^4$)

(a) Baseline
(b) Flow control ($V_{AC}=\pm 2.0 \text{kV}$)
(c) Flow control ($V_{AC}=\pm 2.8 \text{kV}$)
(d) Flow control ($V_{AC}=\pm 4.0 \text{kV}$)

Fig. 23 Turbulence intensity distributions at various DBD-PA input voltages (PA: position B) ($U_{MS}=6.3 \text{ m/s, } Re=4.7 \times 10^4$)

(a) Baseline
(b) Flow control ($V_{AC}=\pm 2.0 \text{kV}$)
(c) Flow control ($V_{AC}=\pm 2.8 \text{kV}$)
(d) Flow control ($V_{AC}=\pm 4.0 \text{kV}$)
3.4 Distributions of time-averaged velocity and turbulence intensity at higher mainstream velocity, $U_{MS} = 6.3$ m/s (plasma actuator: position B)

Figure 22 shows the time-averaged velocity distributions at various input voltages (baseline, $V_{AC} = \pm 2.0$ kV, $\pm 2.8$ kV, and $\pm 4.0$ kV) at the higher mainstream velocity, $U_{MS} = 6.3$ m/s at the plasma actuator position B. In the flow control case of $V_{AC} = \pm 2.0$ kV in Fig. 22(b), the size of the flow separation region is almost same compared with that at the plasma actuator position A in Fig. 10(b). At $V_{AC} = \pm 2.8$ kV in Fig. 22(c), the separation region is smaller than that in Fig. 10(c). At $V_{AC} = \pm 4.0$ kV in Fig. 22(d), the separation region is considerably smaller than that in Fig. 10(d).

Figure 23 shows the turbulence intensity distributions at various input voltages at the higher mainstream velocity, $U_{MS} = 6.3$ m/s at the plasma actuator position B. In the flow control case of $V_{AC} = \pm 2.0$ kV in Fig. 23(b), the turbulence intensity distribution is similar to that at the plasma actuator position A in Fig. 11(b). As the input voltage is increased, in Figs. 11(b) and (c), the high turbulence intensity region moves closer to the curved wall and the turbulence intensity decreases. The change in the turbulence intensity distributions at the plasma actuator position B is relatively larger than that at the plasma actuator position A.

3.5 Distributions of time-averaged streamwise velocity component and turbulence intensity near trailing edge at higher mainstream velocity, $U_{MS} = 6.3$ m/s, $Re = 4.7 \times 10^4$ (PA: position B)

Figures 24 and 25 show the distribution of the time-averaged streamwise velocity component and turbulence intensity near the trailing edge at the higher mainstream velocity, $U_{MS} = 6.3$ m/s at the plasma actuator position B.

In Fig. 24, the velocity distribution at $V_{AC} = \pm 2.0$ kV (red line) is almost the same as the baseline (black line), which indicates no improvement. The boundary layer thickness is approximately 22 mm. At $V_{AC} = \pm 2.8$ kV (orange), the velocity distributions in the boundary layer increases, and the shape of the velocity distributions in the boundary layer becomes more convex than that at the plasma actuator position A in Fig. 16. As the input voltage is increased at $V_{AC} = \pm 4.0$ kV (blue), the velocity in the boundary layer slightly increases.

In Fig. 25, as the input voltage is increased, the width of the high turbulence intensity region decreases. The maximum turbulence intensity decreases gradually from 16% at the baseline to 12.5% at $V_{AC} = \pm 4.0$ kV.

3.6 Effects of different plasma actuator setting positions A and B on boundary layer parameters at higher mainstream velocity, $U_{MS} = 6.3$ m/s

3.6.1 Boundary layer displacement thickness and momentum thickness at trailing edge

Figure 26 shows the displacement thickness, $\delta_1$, of the boundary layer near the trailing edge at the two plasma
actuator positions, A and B. It should be noted that there is a difference between the baseline results for position A and position B, because the plasma actuator mounting influences the flow. At the plasma actuator position A (purple line) located immediately behind the flow separation point, the displacement thickness is gradually reduced by 26% at ±4.0 kV. At the plasma actuator position B (light blue line) located immediately before the flow separation point, the displacement thickness is reduced by 49% at ±4.0 kV.

Figure 27 shows the momentum thickness, $\delta_2$, of the boundary layer near the trailing edge at the two plasma actuator positions. At the plasma actuator position A (purple line), the momentum thickness is reduced by only 7% at ±4.0 kV. At the plasma actuator position B (light blue line), the momentum thickness is reduced by as much as 42% at ±4.0 kV.

3.6.2 Boundary layer shape factor at trailing edge

Figure 28 shows the boundary layer shape factor $H_{12}$ ($= \delta_1/\delta_2$) near the trailing edge at the two plasma actuator positions, A and B. The shape factor at both the plasma actuator positions A and B remains within the intermittently detached region ($2.2 \leq H_{12} \leq 4.0$). However, the shape factor at position B is slightly smaller (close to the attached boundary layer) than that at position A.

3.6.3 Total pressure loss estimation

Figure 29 shows the estimated total pressure loss, $C_{Pl}$, estimated from the boundary layer displacement thickness, $\delta_1$, and momentum thickness, $\delta_2$. At the plasma actuator position A (purple line), the total pressure loss is reduced by 16% at ±4.0 kV. At the plasma actuator position B (light blue line), the total pressure loss is reduced by as much as 47% at ±4.0 kV.

Although the experiment is only conducted at $U_{MS} = 6.3$ m/s, these results show that the plasma actuator position B located immediately before the flow separation point is more suitable than the plasma actuator position A located immediately behind the flow separation point, for the reduction of flow separation. This corresponds to the result of CFD study by another research group (Bell et al., 2015).

4. Conclusions

Dielectric barrier discharge plasma actuators were used for the active control of flow separation on the simulated suction surface of a turbine blade at three mainstream velocities, $U_{MS} = 2.2$ m/s, 4.1 m/s, and 6.3 m/s, corresponding to
the low Reynolds number conditions of $Re = 1.7 \times 10^4$, $Re = 3.1 \times 10^4$, and $Re = 4.7 \times 10^4$, respectively. The flow separation was induced on a curved plate installed in the measurement section of a low-speed wind tunnel. Instantaneous and time-averaged two-dimensional velocity field was measured using a particle image velocimetry system. The amplitude of input voltage for the plasma actuator was changed from $\pm 2.0$ kV to $\pm 4.0$ kV. At the lower mainstream velocity, $U_{MS} = 2.2$ m/s ($Re = 1.7 \times 10^4$), the separated flow induced on a curved wall was significantly reduced by the flow control using the plasma actuator. The effect of flow control by the plasma actuator was gradually reduced at the higher mainstream velocities, $U_{MS} = 4.1$ m/s and 6.3 m/s ($Re = 3.1 \times 10^4$ and $4.7 \times 10^4$). At $U_{MS} = 6.3$ m/s, the flow control effect was improved by changing the position of the plasma actuator. When the plasma actuator was positioned immediately before the separation point, it exhibited better flow control effects than when positioned immediately behind the separation point.

**Nomenclature**

- $CP_t$: total pressure loss coefficient
- $f_p$: frequency of input voltage
- $H_{12}$: shape factor ($= \delta_1/\delta_2$)
- $L$: streamwise length of curved wall, 100 mm
- $Re$: Reynolds number
- $Tu$: turbulence intensity
- $t$: thickness of trailing edge, 1.9 mm
- $U$: absolute velocity
- $U_{MS}$: mainstream flow velocity
- $U_x$: streamwise velocity
- $u_x'$: random fluctuation (turbulence) component of streamwise velocity
- $U_y$: vertical velocity
- $u_y'$: random fluctuation (turbulence) component of vertical velocity
- $V_{AC}$: amplitude of input voltage
- $w$: flow passage width at trailing edge, 60 mm
- $x$: streamwise (horizontal) distance
- $y$: vertical distance

Fig. 28: Shape factor $H_{12}$ near trailing edge ($U_{MS} = 6.3$ m/s, $Re = 4.7 \times 10^4$)

Fig. 29: Estimated total pressure loss ($U_{MS} = 6.3$ m/s, $Re = 4.7 \times 10^4$)
δ₁: boundary layer displacement thickness
δ₂: boundary layer momentum thickness

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