Investigation on performance characteristics of dielectric discharge plasma actuator using pulsed-dc waveform

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Abstract
Dielectric Barrier Discharge Plasma Actuator (DBDPA) is one of active flow control devices, which generates a wall-surface jet utilizing atmospheric discharge. However, the enhancement of the jet is indispensable for application to high Reynolds number flow because the flow speed is typically only up to several meters per second. In recently, it was reported that a Pulsed-DC voltage waveform can drastically improve the jet thrust (McGowan et al., 2016). In the Pulsed-DC waveform, the high DC voltage rapidly drops to zero and gradually recover. In the original idea, the DC high voltage is applied to the top electrode and the Pulsed-DC waveform is applied to the bottom electrode. In this study, firstly, we conduct experiments using the same method proposed by the previous study, and next, the DBDPA, in which the top electrode is powered by the Pulsed-DC waveform and the bottom electrode is electrically grounded, is investigated. Finally, we propose a new waveform which is a sinusoidal voltage with periodical pulsed-earthing. As a result, the DBDPA with Pulsed-DC voltage waveform cannot generate strong wall-surface jet, and on the other hand, the proposed waveform generates a significant jet. Even though its strength is the same magnitude as that by the simple sinusoidal waveform, it is confirmed that the jet thrust is enhanced at phases before and after the pulsed-earthing; the tentative thrust increment is up to 32 %.

Keywords: DBD plasma actuator, Pulsed-DC waveform, Pulsed voltage changing, PIV measurement, Thrust

1. Introduction
Dielectric Barrier Discharge Plasma Actuator (DBDPA) attracts much attention as an active flow control device (Roth et al., 2000, Corke et al., 2007, 2010, Liu et al., 2008). It is composed of two electrodes separated by a dielectric as shown Fig. 1. Atmospheric discharge can be generated by applying AC high voltage between the electrodes and generate plasma over the dielectric surface. The plasma is accelerated by the electric field and collide with neutral molecules. The momentum transfer due to the particle collisions leads to the generation of body force which acts on the ambient neutral gas. And, a surface jet is generated because of “body force generation”. DBDPA has many advantages over conventional devices such as no-moving mechanical parts and active controllability by electrical signal. Therefore, many engineering applications of DBDPA to fluidic devices are expected; flow separation control over an airfoil (Corke et al., 2009, 2011, Fujii, 2014), a wind turbine (Matsuda et al., 2017) and so on. However, the control effect decreases in higher Reynolds number flow (higher mainstream velocity) because the flow speed of the induced jet is typically only up to several meters per second. Drastic enhancement of the performance is indispensable to expand its applicability in practical use.

A number of researches for the performance enhancement have been conducted through various approaches (see the review paper; Benard and Moreau, 2014). Especially, a tri-electrode plasma actuator was proposed and reported to achieve drastic performance improvement. The thrust force is up to ten times larger than that of the conventional type (Moreau et al., 2008, Matsuno et al., 2016, Nishida, et al., 2017). It has an additional exposed electrode on the opposite side of the AC-high-voltage electrode, and DC high voltage is applied to the third electrode. However, it has some
disadvantages. Firstly, the practical applications are limited because the induced jet is vertically deflected and the jet behavior is difficult to be controlled. Secondly, when the applied voltage amplitude exceeds the threshold value, the discharge mode is easily transit to the arc type between the AC and DC electrode. The arching results in break-down of the actuator. On the other hand, the optimization of applied voltage waveform is effective approach because it does not need any additional power supplier and changes in the actuator geometry. The effects of voltage waveform on the performance have been studied by many researchers. Enloe et al. (2004) and Abe et al. (2007) experimentally investigated the thrust force generation for a sinusoidal, triangular, sawtooth and other waveforms derived from these basic waveforms. They reported that larger thrust was obtained by the sawtooth waveform with longer negative-going voltage period. Benard et al. (2012) evaluated the thrust-to-power ratio for a sinusoidal, square and sawtooth waveform, and reported that the sinusoidal waveform could generate the highest performance. Kotsonis et al. (2012) proposed an asymmetric waveform which is composed of sinusoidal and square waveform. They reported that it could enhance the thrust by about 45 % compared to the simple sinusoidal waveform. Sekiya et al. (2016) proposed a waveform which has a gradual and steep voltage slope period in each negative and positive-going voltage half-cycle. As a result, they reported that their waveform could enhance the thrust by 69 % compared to the sinusoidal one. As mentioned above, some researchers successfully proposed effective waveforms. However, the improvement is only up to about 1.7 times larger in the thrust, and it is not sufficient for the practical use in airplanes and turbines.

In 2016, the utilization of Pulsed-DC waveform was proposed by McGowan et al. (2016). In their method, a DC power supply is used instead of the AC power supply. DC high voltage is applied to the top electrode and the Pulsed-DC waveform is applied to the bottom electrode as shown Fig. 2. The Pulsed-DC waveform can be generated by periodically earthing the electrode powered by DC high voltage (the schematic of the circuit is shown in Fig. 3). In the Dielectric-Barrier-Discharge, the time variation of applied voltage is needed for discharge generation (the DC voltage cannot generate continuous discharge). In contrast, the DC voltage is more effective for the body force generation because it can accelerate the plasma constantly in constant strong electric field. The concept of the Pulsed-DC voltage is that dense plasma is generated in a short period by exponential voltage change of the pulsed earthing. And the body force generation is achieved effective by the acceleration of the dense plasma in the DC period. Note that, in the conventional DBDPA powered by a sinusoidal voltage, the plasma generation and acceleration (body force generation) take place simultaneously. They measured the thrust force utilizing an electronic balance as shown in Fig. 4. Their measurement results are plotted in Fig. 5; in this experiment, the voltage frequency is 1 kHz and the dielectric is made from polyimide films with the thickness of 4 mil (= 0.1016 mm). Figure 5 shows that the Pulsed-DC waveform can generate much larger thrust than the typical AC waveform.

![Fig. 1 Schematic figure of DBDPA.](image)

![Fig. 2 Example of Pulsed-DC waveform (McGowan et al., 2016).](image)

![Fig. 3 Electrical circuit for DBDPA by Pulsed-DC voltage (McGowan et al., 2016).](image)
The working mechanisms of a DBDPA have been studied by many researchers by both numerical simulations and experiments (Boeuf et al., 2009, Nishida and Abe, 2011, Enloe et al., 2016). From the consideration about the working mechanism of DBDPA, the discharge is driven by the potential difference between the top electrode and the dielectric surface (Fig. 6 (a)). As soon as the discharge occurs, the plasma collides with the dielectric surface, and charges the surface. The surface charge weakens the electric field strength (Fig. 6 (b)), and the discharge stops; that is, the body force generation stops. When AC voltage is applied, the electrode potential tentatively changes and the electric field strength is kept. Therefore, the discharge (the body force generation) is sustained (Fig. 6 (c)). On the other hand, when DC voltage is applied, the electrode potential does not change. The electric field strength is kept at low amplitude (Fig. 6 (d)), and it is considered that significant discharge (i.e. the body force generation) cannot be generated. In fact, we cannot explain why the Pulsed-DC waveform generates such large thrust based on the physical consideration because it has long period of DC voltage.

In this study, firstly, for verifying the results reported by McGowan et al., we conduct experiments using the same method proposed by them. The top and bottom electrode is powered by the DC high voltage and the Pulsed-DC waveform, respectively. Next, for investigating the characteristics of DBDPA powered by Pulsed-DC waveform in more detail. We investigate a DBDPA with top electrode powered by the Pulsed-DC waveform and electrically-grounded bottom electrode. In addition, we try to find out a new method utilizing “pulsed-earthing” voltage waveform, which is different from the proposed method in the previous study. We propose a sinusoidal waveform with pulsed-earthing. In the previous study, the performance of DBDPA was evaluated by the thrust measurement. However, it is not so easy to correctly measure the thrust, because it is difficult to completely eliminate several kinds of measurement error such as electrostatic force (Ashpis and Laun, 2017). Moreover, the thrust measurement provides only the time-averaged and volume-integrated characteristics of the performance. Therefore, in this study, we obtain the flow field using the PIV (Particle Image Velocimetry) measurement, and the thrust is evaluated by numerically integrating the momentum flux obtained in the PIV measurement results.

Fig. 6 Body force generation mechanism of DBDPA.
2. DBD plasma actuator powered by Pulsed-DC waveform

2.1 Experimental setup

We designed and fabricated an electrical circuit as shown in Fig. 7 to generate a Pulsed-DC waveform. High DC voltage was applied by a DC power supply (HAR-30R10, MATSUSADA PRECISION), and IGBTs (IXBF20N360, IXYS) switches ON and OFF of the electrical grounded line connection. IGBTs were controlled by narrow trigger pulse signal from a function generator (AFG2021, Tekronix). The electrode was periodically earthed for very short period (1 µs). The applied voltage was monitored by an oscilloscope (HDO4034, TELEDYNE LECROY) through a high voltage probe (PHV4002-3-RO, IWATSU).

![Fig. 7 Electrical circuit for applying the Pulsed-DC waveform](image)

The PIV measurement was conducted to obtain the flow field around the DBDPA. The PIV system is composed of a double pulse Nd-YAG laser whose wavelength is 532 nm and output power is 30 mJ/pulse (Litron Lasers, NanoS30-15PIV), and a CCD camera with resolution of 1296×966 pixel (SAR-PIV). The DBDPA was driven in a stainless chamber, and tracer particles generated by incense sticks were seeded inside the chamber. A single focus lens (Nikon, Micro-Nikkor 105 mm f/2.8) and a band pass filter were set on the CCD camera. The center wavelength of a band pass filter is 532 nm and the half width of a band pass filter is 15~20 nm; it is adjusted to the wavelength of the laser. The PIV sampling rate was 10 Hz. The time-averaged flow field was calculated from 200 sets of flow field data. The PIV system can be synchronized with the power supply system of a DBDPA, and the flow field phase-locked to the voltage waveform can be obtained. In this experiment, the phase-averaged flow field was calculated from 200 sets of data.

![Fig. 8 PIV measurement system](image)

2.2 Experimental conditions

The dielectric layer of DBDPA was made from polyimide tapes with total thickness of 0.16 mm (0.08 mm/sheet × 2) and both electrodes of DBDPA are made from copper tape with thickness of 0.03 mm (The chord length is 10 mm for the top electrode and 20 mm for the bottom electrode). The span length of DBDPA is 130 mm.

The experimental conditions are summarized in Table 1. Variations of the power supply system are shown in Fig. 9.
P-DC1 (Fig. 9(a)) is the same driving method as used by McGowan et al.; the top electrode was powered by DC high voltage and the bottom one was powered by the positive Pulsed-DC voltage. In P-DC2 type (Fig. 9(b)), the positive Pulsed-DC voltage waveform was applied to the top electrode and the bottom one was electrically grounded. In P-DC3 type, the negative Pulsed-DC voltage was applied to the top electrode. In P-DC2 and P-DC3 types, the voltage difference between the top and bottom electrode is larger than that in P-DC1 type.

Four kinds of Pulsed-DC waveform, named Wave1, 2, 3 and 4 shown in Fig. 10, were used in this study. Wave1 and 2 are positive Pulsed-DC voltage, and Wave 3 and 4 are negative one. The voltage rising time from 0V is different between Wave1-2 and Wave 3-4. It can be changed by changing the resistor in Fig. 7. In addition, a simple sinusoidal waveform was also experimented for comparison (* in Table 1). A sinusoidal signal from the function generator (AFG2021, Tektronix) was amplified by 1000 times using a high voltage amplifier (MODEL 10/40A, Trek).

| Table 1  | Experimental conditions. |
|----------|-------------------------|
|          | Top electrode           | Bottom electrode          |
| P-DC1    | DC 7 kV                 | Pulsed-DC waveform (Wave1) 6.5kV, 3 kHz |
| P-DC2    | Pulsed-DC waveform (Wave1, Wave2), 6.5kV, 3kHz | 0V (grounded) |
| P-DC3    | Pulsed-DC waveform (Wave3, Wave4), -6.5kV, 3kHz | 0V (grounded) |
| *        | Sinusoidal waveform, 6.5kV, 3kHz | 0V (grounded) |

2.3 Experimental results

Firstly, the result of P-DC1, which is the same method as used in the previous study (McGowan et al., 2016), is shown. Figure 11 shows the time-averaged flow fields by (a) the Pulsed-DC waveform (calculated from 86 sets of data) and (b) the sinusoidal waveform. The conventional DBDPA powered by the sinusoidal voltage generates a wall-surface jet as shown in Fig. 11 (b). However, when the DBDPA is driven by the P-DC1 power supply system, apparent wall-surface jet is not generated as shown Fig. 11 (a). Figure 12 shows the streamwise velocity (= \( u \) [m/s]) profile at two streamwise locations (at \( x = 5 \) mm and \( x = 9 \) mm). It can be apparently observed that a significant jet is not generated in P-DC1. For investigating the flow field behavior of P-DC1, the time-series instantaneous flow fields obtained at 10 Hz are shown in Fig. 13. In this experiment, the first measurement timing \( t_1 \) cannot be specifically identified, because the PIV system was not synchronized with the power supply system. However \( t_1 \) is within 0.1 second from the start of DBDPA actuation. As observed in Fig. 13, a steady wall-surface jet is not generated and the flow unsteadily fluctuates. As just described, the P-DC1 type could not generate a wall-surface jet. However, the appearance of discharge was clearly observed. Figure 14 shows the plasma photo emission of (a) P-DC1 (the applied voltage amplitude is 5 kV) and (b) the sinusoidal voltage (the applied voltage amplitude is 4.5 kV). Although the photo emission of P-DC1 is weaker than that of the sinusoidal voltage, apparent photo emission can be observed in Fig. 14 (a). Therefore, it is expected that plasma generation was successfully conducted by the pulsed voltage change, but the body force generation was quite small in the DC voltage period.

Our electric circuit is different from that used by McGowan et al.: MOSFET switches were used by McGowan et
al., but IGBT switches are used in this experiment. We checked the voltage waveform using the high voltage probe. However, the probe do not have the capacity to resolve detail voltage profile in nanoseconds, and therefore there is a possibility that the voltage profile during the pulsed earthing is different between in this experiment and that by McGowan et al. Unfortunately, it is difficult to make further discussions, because details of the electric circuit were not described in their papers, and as far as we know, there is no published paper that other researchers succeeded in reproduction of the results by McGowan et al.

(a)                                (b)

Fig. 11  Time-averaged flow fields around the DBDPA; (a) P-DC1, (b) the sinusoidal waveform.

(a)                              (b)

Fig. 12  $x$-directional velocity profiles of P-DC1 and sinusoidal voltage; (a) $x = \text{approximately } 5.00\,\text{mm}$, (b) $x = \text{approximately } 9.00\,\text{mm}$.

(a)                                (b)

Fig. 13  Time series instantaneous flow field of P-DC1-type DBDPA.
Next, the results of P-DC2 and P-DC3 are shown. In these experiments, the Pulsed-DC voltage is applied to the top electrode and the bottom electrode is electrically grounded. Figure 15 shows the time-averaged flow field generated by Wave 1 to 4, and that by the sinusoidal voltage is also shown in the figure for comparison. As clearly observed in the figure, the steady wall-surface jet is generated in P-DC2 and P-DC3 type DBDPA. It can be considered that large voltage difference between the top and bottom electrode results in the body force generation. However, the jet strength by P-DC2 and P-DC3 is apparently weaker than that by the sinusoidal voltage. In order to quantitatively evaluate the jet strength, the thrust and the local maximum flow velocity are shown in Table 2 for all experimental cases. The thrust was numerically calculated based on the momentum conservation in a control volume. The equation is shown in equation (1). The control volume for the momentum balance equation is shown in Fig. 16. Where $\rho$ is density, $u$ is $x$-directional velocity and $v$ is $y$-directional velocity. In this experiment, the standard deviations calculated from 200 instantaneous flow field date were indicated together with the calculation results of thrust. The standard deviation indicates the influence of velocity fluctuation. Figure 17 shows the comparison of $x$-directional velocity profile at two $x$ locations as waveform changing. Although the contribution of the pressure distribution is not taken into account, another investigate has reported that it can be minimized. Because pressure can be considered uniform and equal, if the control volume boundaries are far enough from the bulk of the plasma body force (Kotsonis et al., 2011). Therefore, the thrust from the velocity distributions is expected to be good index for evaluating the performance of the actuator. Fig. 16(b) shows the control volume for calculation. As observed in Table 2 and Fig. 17, the negative Pulsed-DC voltage waveforms (P-DC3) generates larger thrust and higher flow velocity than those by the positive one (P-DC2). In addition, longer voltage-rising time from 0 V generates larger thrust and higher velocity. Therefore, it can be concluded that temporal change in voltage is significant for the body force generation. This means that the DC voltage period of the Pulsed-DC waveform is not effective for the body force generation. Furthermore, it is generally known that the negative going-voltage period is more effective to generate the body force than the positive-going voltage period (Benard et al., 2013). Therefore, it can be considered that the negative Pulsed-DC waveforms are more effective. However, the thrust and maximum local flow velocity generated by the Pulsed-DC waveforms are much smaller than that generated by the sinusoidal voltage.
Fig. 15  Time-averaged flow field around the DBDPA driven by P-DC2, P-DC3 and the sinusoidal voltage.

(a) Definition of letters in equation (1).        (b) Control volume for calculation.

Fig. 16  The control volume for the momentum balance equation.

$$ F = \rho \int_{bc} u^2 dy + \rho \int_{cd} uv dx - \rho \int_{da} u^2 dy $$  \hspace{1cm} (1)

Fig. 17  $x$-directional velocity profiles of P-DC2, 3 and sinusoidal voltage; (a) $x = \text{approximately } 5.00\text{mm}$.  (b) $x = \text{approximately } 9.00\text{mm}$.

| Wave       | Thrust (Standard deviation) [mN/m] | Maximum velocity [m/s] |
|------------|------------------------------------|------------------------|
| Wave1      | 0.22 ($\pm$ 0.16)                 | 0.55                   |
| Wave2      | 0.22 ($\pm$ 0.14)                 | 0.53                   |
| Wave3      | 0.44 ($\pm$ 0.35)                 | 0.89                   |
| Wave4      | 0.93 ($\pm$ 0.54)                 | 1.00                   |
| Sinusoidal | 7.64 ($\pm$ 4.35)                 | 3.68                   |
3. Pulsed-Earthing sinusoidal voltage

3.1 Proposal of new waveform

Both effective generation and acceleration of plasma are indispensable for strong body force generation. From the consideration based on the results of this study, it is expected that the pulsed change in voltage is effective for plasma generation. On the other hand, (gradual) temporal change in voltage is effective for the plasma acceleration. Therefore, we propose a new waveform shown in Fig. 18; the new voltage waveform is a sinusoidal voltage with periodical pulsed-earth. When a sinusoidal voltage is applied, the generation and acceleration of plasma take place simultaneously through whole one cycle (Benard et al., 2013). In the proposed voltage waveform, additional plasma generation by the pulsed-earth can be expected. Moreover, it can be also expected that the pulsed-earth of the electrode clears the charging on the dielectric surface and recovers the electric field strength; i.e. the discharge can be reinforced (Sato et al., 2017). If this concept works well, it is expected that larger body force generation can be achieved even by lower voltage amplitude.

![Fig. 18 A new waveform which is proposed by us.](image1)

3.2 Experimental setup and conditions

An electrical circuit designed and fabricated for this experiment is shown in Fig. 19. The pulsed voltage change to zero (pulsed-earth) was at the timing of the negative and positive peak voltage of the sinusoidal waveform whose amplitude is $6.5kV_p$ and frequency is 1 kHz. The PIV sampling rate is 9 Hz. For comparison, the simple sinusoidal voltage with voltage amplitude of $6.5kV_p$ and frequency of 1 kHz was also experimented. The configuration and construction material of the DBDPA was the same as used in the previous chapter. Note that thickness of the top electrode and bottom electrode was 0.05 mm, and the shape of the top electrode was serrate.

![Fig. 19 Electrical circuit for Pulsed-Earthing sinusoidal voltage.](image2)

3.3 Experimental results

Figure 20 shows the time averaged flow fields which are calculated from 200 sets of flow field data. The comparison of $x$-directional velocity profile at two $x$ locations is shown in Fig. 21. Obvious difference cannot be observed between the flow field by the proposed voltage waveform and that by the simple sinusoidal voltage, but it can be observed in Fig. 21 that the maximum velocity is slightly larger in the sinusoidal waveform. In order to qualitatively compare these two voltage waveforms, the thrust and maximum velocity are summarized in Table 3 (the thrust of sinusoidal voltage is different between in Table 2 and 3. This is because the shape of the electrode is different; liner in
Table 2 and serrate in Table 3). Both results show almost the same value, and obvious enhancement of the performance is not observed in the pulsed-earthing sinusoidal voltage.

In order to investigate the flow field by the pulsed-earthing sinusoidal voltage in more detail, the phase-locked flow fields were obtained before and after the pulsed-earthing at the positive voltage peak. Figure 22 and 23 shows the phase-averaged flow fields; note that the timing of the pulsed-earthing is 0.25 ms. The comparison of $x$-directional velocity profile at two $x$ locations is shown in Fig. 24. Figure 24 shows that the peak velocity of the pulsed-earthing sinusoidal wave is equal to or larger than that of the sinusoidal one. Moreover, the peak velocity of the pulsed-earthing waveform temporary fluctuates. Before the pulsed-earthing (at 0.200 ms), the peak velocity of the pulsed-earthing waveform is larger than that of the sinusoidal one. Although, at 0.255 ms, the velocity profile does not change immediately by the pulsed-earthing. But the peak velocity becomes slightly smaller, after some time passing from the pulsed-earthing (at 0.275 ms). However, the peak velocity becomes larger again, at the end-phase of the positive-going voltage half cycle (at 0.300 ms). Figure 25 shows the thrust calculated from the flow field. The standard deviation in the figure indicates the influence of velocity fluctuation of each velocity fields at one phase time. The fluctuation of the calculated thrust roughly agree to the trend of the peak velocity fluctuation which shown in Fig.24. The results of the simple sinusoidal voltage are also plotted for comparison, and voltage waveforms are overlapped for convenience. The thrust estimated from the phase averaged flow in Fig. 25 becomes smaller than the time-averaged thrust calculated over the whole period of AC voltage (in Table 3). This is because the phase-averaged flow fields were obtained only at the end-phase of the positive-going voltage half cycle. It is generally known that larger body force (thrust force) is generated during the negative-going voltage half cycle. As observed in Fig. 25, the thrust by the pulsed-earthing sinusoidal voltage is larger than the thrust by the sinusoidal voltage at all phases. The enhancement of the thrust is up to 32%. However, the thrust time-averaged over one voltage cycle is not so different between the pulsed-earthing and simple sinusoidal voltage (in Table 3). Therefore, the thrust at phases out of the measurement range should decreases. We need to measure the phase-locked flow field in more detail over whole one voltage cycle.

In the original concept, the pulsed-earthing is expected to contribute to the performance improvement by enhancing the plasma generation. If this mechanism works as expected, the thrust must be enhanced only after the pulsed-earthing. However, as shown in Fig. 25, the thrust enhancement is observed both before and after the pulsed-earthing. The mechanism cannot be clarified at this research stage, and further studies including numerical simulations of discharge plasma evolution are required. In future works, the effects of the timing and number of pulsed-earthing needs to be investigated in detail, in order to constantly enhance the performance of DBDPA.
Table 3  Thrust and maximum velocity

|                  | Thrust (Standard deviation) [mN/m] | Maximum velocity [m/s] |
|------------------|-----------------------------------|------------------------|
| Proposed waveform| 10.6(±1.09)                       | 3.98                   |
| Sinusoidal       | 10.5(±0.78)                       | 4.14                   |

Fig. 22  The phase-locked flow fields of sinusoidal waveform.

Fig. 23  The phase-locked flow fields of a proposed waveform.

Fig. 24  Phase averaged $x$-directional velocity profile of the proposed and sinusoidal voltage; (a) $x = 5.13$mm. (b) $x = 9.19$mm.
4. Conclusions

The characteristics of flow fields generated by the DBDPA powered by the Pulsed-DC voltage were experimentally investigated using the PIV measurement. In addition, aiming for more performance enhancement, we proposed a new voltage waveform, which is the sinusoidal voltage with pulsed-earthing. As a result, following conclusions were obtained.

1. Our experiment could not reproduce drastic thrust enhancement reported in the previous study; it generated only quite small jet.
2. When the Pulsed-DC voltage was applied to the top electrode and the bottom one was electrically grounded, it generated a wall-surface jet. However, its strength was smaller than that by the sinusoidal voltage. It is considered that temporal change in voltage is indispensable for effective body force generation.
3. The sinusoidal waveform with pulsed-earthing, which was proposed in this study, could generate the wall-surface jet, however large thrust enhancement could not be obtained from the time-averaged viewpoint. In phases before and after the pulsed-earthing, it was confirmed that the thrust was enhanced; the tentative thrust increment was up to 32%.

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