Discharge Phenomena of Multi-Phase AC Arc for In-Flight Processing

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Abstract: Multi-phase AC arc is suitable for the in-flight melting treatment of the granulated glass raw materials because of its large plasma volume, low gas velocity, and high energy efficiency. The discharge mechanism of the six-phase AC arc was investigated by a high-speed video camera observations synchronized with an arc discharge voltage measurements. The image analyses of high temperature distributions revealed that uniform high temperature distributions were broadened with increasing the number of the phase.

Keywords: Multi-phase AC arc, In-flight processing, Image analysis

1. Introduction

The conventional single-phase and the three-phase AC power supplies have a characteristic of intermittent discharge which limits the application of arc systems [1-2]. To obtain a more effective arc reactor, the concept of arc generation controlled by rotated magnetic field or by multiple electrode configurations has been proposed [3-4]. However, these power sources for the arc generation were accomplished by DC power supply. Therefore the cost of the apparatus was expensive for converting AC to DC.

A multi-phase AC power supply has been developed [5] to overcome above mentioned problems of the conventional arc generation. The important advantage of this system was larger number of discharging paths among the electrodes than the case of the single-phase and the three-phase systems. Therefore, the arc discharges among the electrodes always exist, which leads to a stable arc generation [7].

An innovative in-flight processing technology with multi-phase AC arc was developed for waste treatment [6] and synthesis of nano-sized materials [7]. Multi-phase AC arc was also suitable for the in-flight melting of granulated glass raw materials because of its large plasma volume, low gas velocity, and high energy efficiency [8-9]. However, only few researches about the characterization of the discharge mechanism of the multi-phase AC arc have been reported. In order to enhance the performance of the in-flight treatment, the discharge mechanism of the multi-phase AC arc should be understood.

The objective of this paper is to investigate the discharge mechanism of the six-phase AC arc. The high-speed video camera observations synchronized with voltage measurements were conducted. Arc behaviors in electrodes region and plasma luminance fluctuation were estimated by image analyses.

2. Experimental setup

The schematic diagram of a thermal plasma reactor generated by the six-phase AC arc power supply is shown in **Figure 1**. Tungsten with thorium (2wt %) electrodes 3.2 mm in diameter shielded by argon (99.99%) for preventing the oxidation were installed inside of the torches. City water was used to cool the electrodes and the jacket at 1.5 slpm of the flow rate.

The voltage applied between each electrode can be described by following equation,

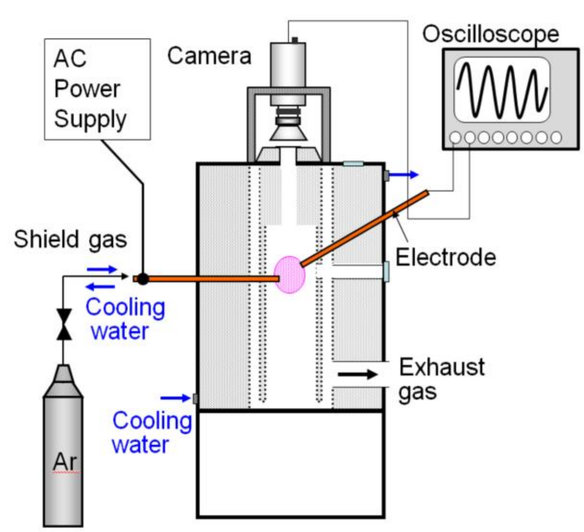

Figure 1. Schematic diagram of experimental setup of the six-phase AC arc.

$$V_i = V_m \sin\left(\omega t - \frac{(i-1)}{6}\pi\right),\ i = 1 \ldots .6 \quad (1)$$

where, V_m is the amplitude, ω the angular frequency and the argument ωt of the sine gives the phase of the voltage. Each voltage has sixty degrees of phase shift to the neighboring electrodes. The power supply of the six-phase AC arc discharge was explained in details [7].

The discharge behavior of the six-phase AC arc was characterized by the high-speed video camera (HSV-500C, NAC, Japan) installed on the top of the reactor. The voltage and current waveforms of arc discharge were also measured by an oscilloscope synchronized with the high-speed video camera observation. Its exposure time and the flame rate were 9 μs and 40,000 fps, respectively.

3. Arc behaviors in electrodes region

Arc behaviors in the case of the six-phase AC arc discharge are complicated because of the rotating magnetic fields caused by the six electrodes affects the Lorenz force acting on the plasma. The high temperature fluctuations caused by arc behaviors in electrodes region were carried out by the image analyses.

Figure 2 presents well known arc images of the two-phase AC arc captured by the high-speed video camera. The arc flows in one direction due to the thermal pinch effect. The analyses of the high-speed video images were carried out to estimate the arc existence area of the two-phase AC arc. The obtained images during a half period (10 ms) were accumulated. Therefore, the accumulated images correspond to the contour maps of the arc existence area (high temperature region), as shown in **Figure 3**.

In the case of the six-phase AC arc, the arc images shown in **Figure 4** indicate the arc movement from its right side to the left side and then return to the right side again. The rotating magnetic fields by the six electrodes affect these arc behaviors mentioned above. The reason of these swing motions will be explained in the next chapter.

The contour maps of the arc existence area in the case of the six-phase AC arc are shown in **Figure 5**. These results indicate that the high temperature region obtained by the six-phase AC arc is wider than that by the two-phase. Therefore, the six-phase AC arc provides an efficient heat source for in-flight melting.

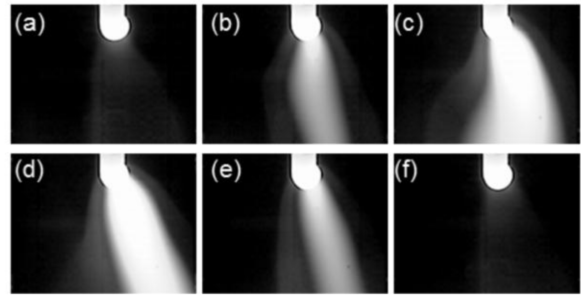

Figure 2. Arc flows of two-phase arc. (a) 0 ms, (b) 2 ms, (c) 4 ms, (d) 6 ms, (e) 8 ms, (f) 10 ms.

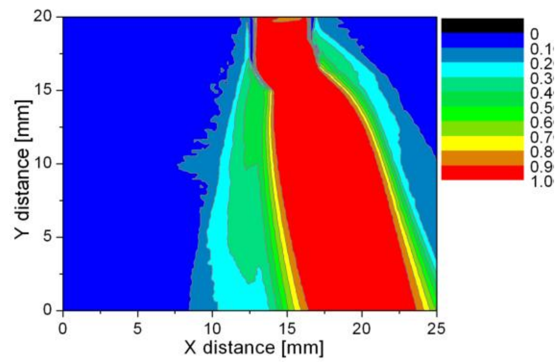

Figure 3. Analyzed image of accumulating the high temperature region in a half period (10 ms).

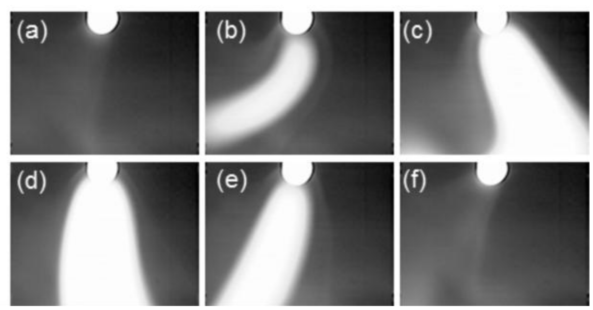

Figure 4. Arc swings of six-phase arc. (a) 0 ms, (b) 2 ms, (c) 4 ms, (d) 6 ms, (e) 8 ms, (f) 10 ms.

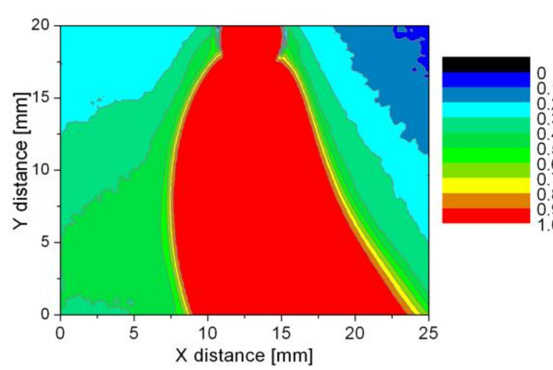

Figure 5. Analyzed image of accumulating the high temperature region in a half period (10 ms).

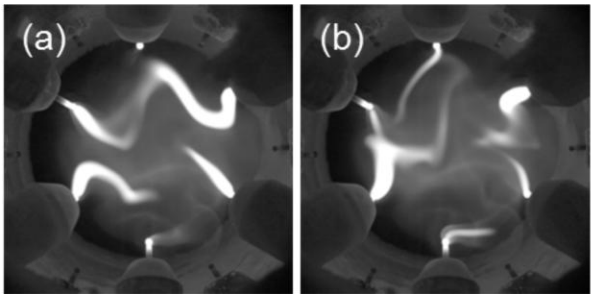

Figure 6. Representative images of six-phase AC arc corresponding to the peak point of the luminance area (a) and bottom point (b).

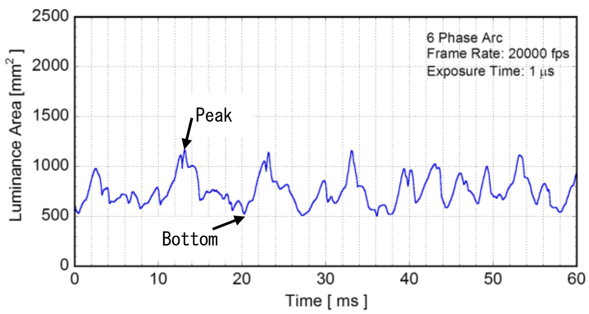

Figure 7. Fluctuation of luminance area of six-phase AC arc.

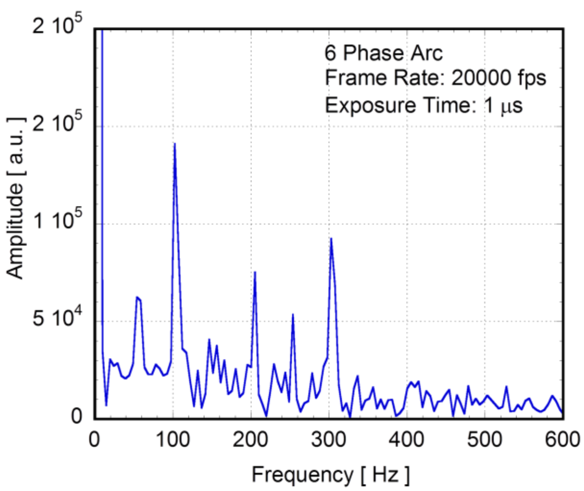

Figure 8. FFT analysis of luminance area of six-phase AC arc.

4 Plasma luminance fluctuations

Plasma fluctuation is one of the most important features in the case of the material processing by the arc discharge. The fluctuation of the luminance area among the electrodes region was estimated in order to evaluate the advantages of the multi-phase AC arc for the in-flight powder heat treatment.

Figure 6 shows the representative images of the six-phase AC arc discharge obtained by the high-speed video camera. These two images indicate the arc paths which are attracted and repelled each other. These motions lead to the periodic swinging motion of arc in the electrodes region mentioned in chapter 3. The luminance area was then calculated from the high-speed video images after the binarization by appropriate threshold value.

Figure 7 shows the fluctuation of the calculated luminance area in the case of the six-phase AC arc. It is notable that the luminance area periodically fluctuates as shown in Figure 6. Furthermore, only two patterns of discharges were produced during the six-phase AC arc discharge, as shown in Figure 6 (a) and (b) which corresponds to the peak point and the bottom point of the luminance area, respectively.

The result of the fast Fourier transfer (FFT) of the luminance area is presented in **Figure 8**. The strongest peak of 100 Hz is originated by the frequency of power source (50 Hz). The peak at 300 Hz indicates the frequency of the characteristics of the arc generation as indicated in Figure 6. These two typical patterns rotate 50 times a second.

5. Stability of arc discharge

The conventional AC arc discharges were unstable due to the existence of two zero-cross points of current in one period. **Figure 9** shows the typical voltage waveform in the case of the two-phase AC arc discharge. The steep voltage changes are observed around the zero-cross points, indicating that the arc discharges are extinguished at those points.

The voltage waveform of the six-phase AC arc is shown in **Figure 10**, where the ideal sinusoidal voltage waveform is also shown for comparison. The observed voltage waveform is similar to the ideal one, compared to that of the two-phase arc shown in Figure 9.

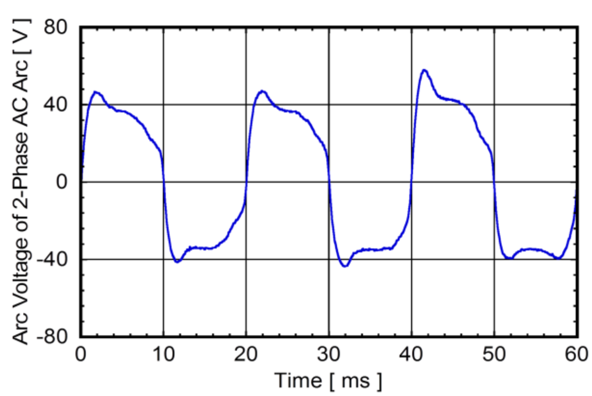

Figure 9. Voltage waveform of two-phase AC arc.

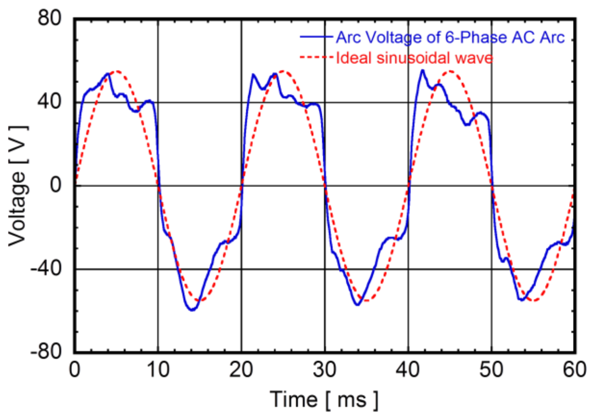

Figure 10. Voltage waveform of six-phase AC arc discharge (blue line) with a sinusoidal waveform (red line).

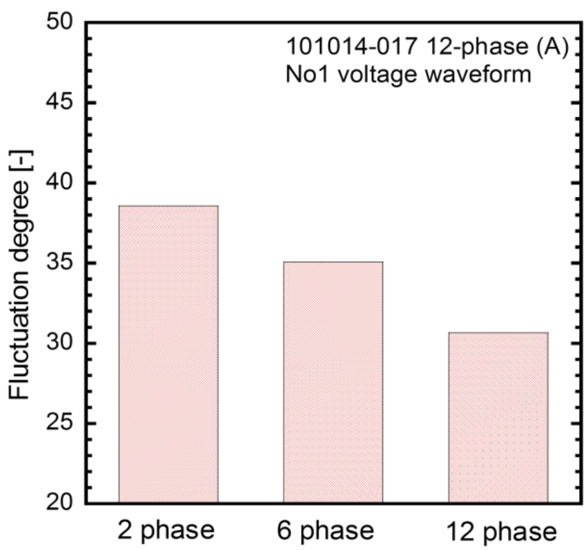

Figure 11. Fluctuation degree of two, six, and twelve phase AC arc.

In section 4, the fluctuation of the luminance area was calculated to evaluate the stability of the six-phase AC arc. Likewise, the fluctuation degree of arc voltage, ε, was defined as

$$\varepsilon = \frac{\sigma}{V_e} \quad (2)$$

where V_e is the effective value of voltage, and σ is the standard deviation defined as follows.

$$\sigma = \sqrt{\frac{1}{T}\int_0^T [V(t) - \langle V_m \sin \omega t \rangle]^2 dt} \quad (3)$$

$V(t)$ is the voltage recorded at time t and $V_m\sin(\omega t)$ is the ideal sinusoidal wave.

The fluctuation degrees for the two, six, and twelve-phase AC arc are shown in **Figure 11**. The fluctuation degree decreases with increasing the phase number. This indicates that an increase in the phase number leads to a decrease in the re-ignition voltage of the AC arc, which results in more stable AC arc.

6. Conclusions

The discharge mechanism of the six-phase AC arc plasma was investigated by the high-speed video camera observations synchronized with the voltage measurements and by the image analyses. Plasma fluctuation degree was introduced to estimate the stability of the six-phase AC arc. An increase of the number of phase leads to the lower fluctuation degree resulting from the reduction of the re-ignition voltage. This indicates the six-phase arc is the more suitable for the in-flight melting than the two-phase arc. A high temperature region was broadened with increasing the number of the phase. Therefore, the six-phase arc provides the generation of large volume of plasma. The swing motions of arc paths were observed in the six-phase AC arc discharge. This was due to the Lorentz force by the arcs among electrodes and by the rotating magnetic fields.

Acknowledgment

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