Discharge Characteristics of Water Plasma with Mist Generation

H. Munekata, M. Tanaka, and T. Watanabe

Department of Chemical Engineering, Kyushu University, Fukuoka, Japan

Abstract: An innovative water plasma torch with mist generation was developed for stable water plasma under atmospheric pressure. The purpose of this study is to investigate the arc fluctuation phenomena in the water plasma torch with mist generation. High-speed camera observation synchronized with arc voltage measurement was performed to understand the arc fluctuation. Results revealed that the arc fluctuation in the developed torch can be classified as perfect restrike mode. Effect of arc current on the discharge characteristics was examined.

Keywords: Thermal plasmas, Arc fluctuation, High-speed camera

1. Introduction

Thermal plasmas have unique advantages such as high enthalpy, high chemical reactivity, and oxidation or reduction atmospheres in accordance with required chemical reactions. Therefore, thermal plasmas are expected to be utilized for decomposition of harmful materials and recovery of useful materials [1].

A non-transferred arc is generated between a cathode and nozzle working as an anode. This type of the arc discharge is suitable for various applications because no external electrodes are required. However, the plasma generation system generally requires complex sub-equipment such as gas-supply and cooling unit. Thus, efficient and simple plasma generation systems have been required for practical application.

The developed torch provides the generation of 100%-water plasma without commercially available steam generator [2, 3]. Water plasma is one of the most attractive thermal plasmas for innovative green technology. This is because the water plasma has a benefit to possess large amount of H, O, and OH radicals. These radicals combine with decomposed components to inhibit the by-products formation. Furthermore, a large amount of syngas, H_2 and CO, can be produced.

In water plasma, liquid water in the reservoir is directly injected into discharge region through stainless steel felt by capillary phenomena. However, the arc stability in this plasma torch is not sufficient due to the unstable water feeding by the stainless steel felt. Therefore, improved water plasma torch with mist generation has been developed to achieve the stable feeding of liquid water into discharge region for an improvement of the arc stability.

Recent studies have revealed the arc fluctuation of the water plasma by high-speed visualization [4]. However, these fundamental phenomena in water plasma with mist generation has not been investigated in spite of their importance. Understanding arc fluctuation phenomena is necessary to apply water plasma with mist generation for waste treatment.

The purpose of this paper is to investigate the discharge characteristics of the innovative water plasma with mist injection. High-speed camera observation with synchronized voltage measurements was carried out to understand arc fluctuation in the non-transferred water plasma torch with mist injection.

2. Experimental

Schematic diagram of water plasma system with mist generation is shown in **Fig. 1**. The plasma torch was a DC non-transferred arc generator of coaxial design with a cathode of hafnium embedded into a copper rod and a nozzle type copper anode. The diameter of hafnium was 1.0 mm. Using hafnium as a cathode material can prevent the erosion and perform a longer operating time in an oxidative atmosphere.

An ultrasonic atomizer at the bottom of the torch atomizes the liquid at a frequency of 2.5MHz. The generated water mist is directly introduced into the discharge region. Water plasma was generated at discharge region by heating and ionization of mist. Simultaneously, the anode is cooled by the water evaporation, thus the torch can be operated in the absence of carrier gases or air injection, cooling-controlled system, and pressure-controlled devices. Therefore, the presented system is a portable light weight system without additional gas supply system and has a higher energy efficiency than 90%.

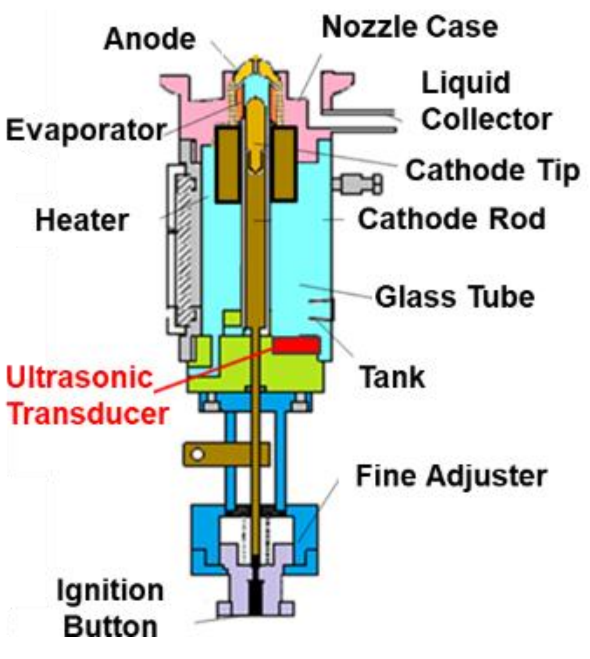

Fig.1. Schematic diagram of water plasma system with mist generation.

Moreover, the generated H, O, and OH radicals in water plasmas are useful for suppressing by-product formation

Schematic diagram for observation of arc fluctuation is shown in **Fig. 2**. Two types of plasma torches were used to compare the discharge characteristics of the plasma torch with and without mist injection. First one is the water plasma torch with mist generation shown in Fig. 1. Another torch without mist generation includes a water feeding system with stainless steel felt. This torch was conventionally utilized in our previous research [4].

Water or 5mol% methanol solution were introduced into the torch. The methanol solution was used as a model substance of organic waste. The arc current was changed in the range from 6.0 A to 9.5 A to investigate the effect of arc current on the arc fluctuation phenomena. The arc voltages were measured by a digital oscilloscope (Scope Corder DL850, Yokogawa) with the sampling interval of 0.46 µs. A high-speed video camera (Phantom Miro LAB110, Vision Research and FASTCAM SA-5, Photron) were used to observe the arc movement at the nozzle exit with a framerate of 2.2×10^5 fps.

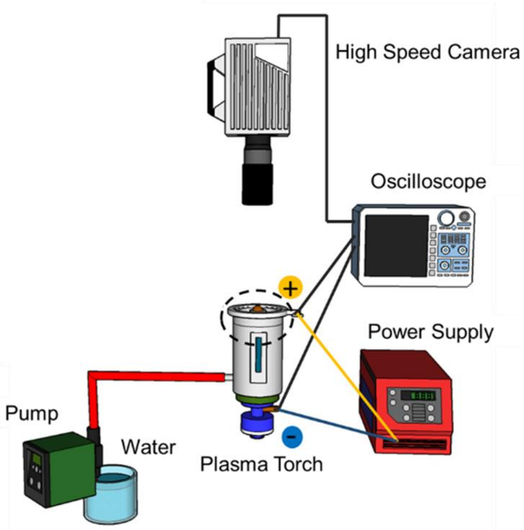

Fig.2. Schematic diagram for observation of arc fluctuation.

3. Results and Discussion

3-1. Effect of mist generation on arc stability

The voltage waveform and the synchronized high-speed snapshots in the water plasma torch with mist generation in **Fig. 3.** A periodic saw tooth shape of the voltage waveform was clearly found in Fig. 3(a). This voltage fluctuation originated in periodical restrike motion of the arc shown in Fig. 3(b). The arc is bent in the axial direction and an anodic arc root appeared on the nozzle surface when the arc comes out from the water plasma torch. The voltage waveform and the synchronized high-speed snapshots in the water plasma torch without mist generation in **Fig. 4**. Repeatability of voltage fluctuation in the water plasma

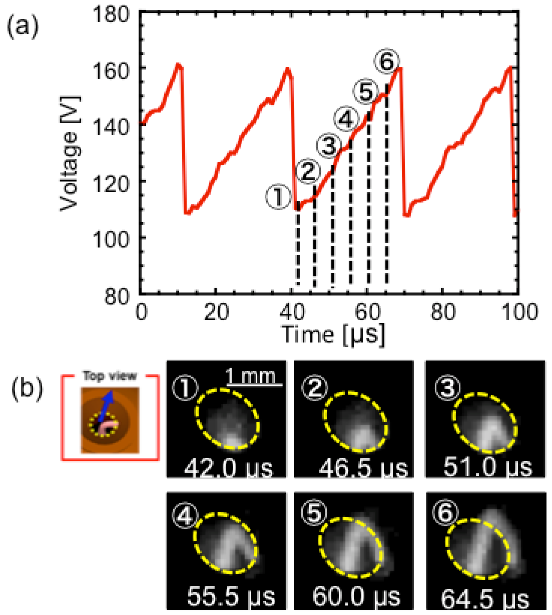

Fig.3. Representative arc voltage waveform (a) and corresponding high-speed snapshots of the arc at nozzle exit (b) at 9.5 A of arc current in the water plasma torch with mist generation.

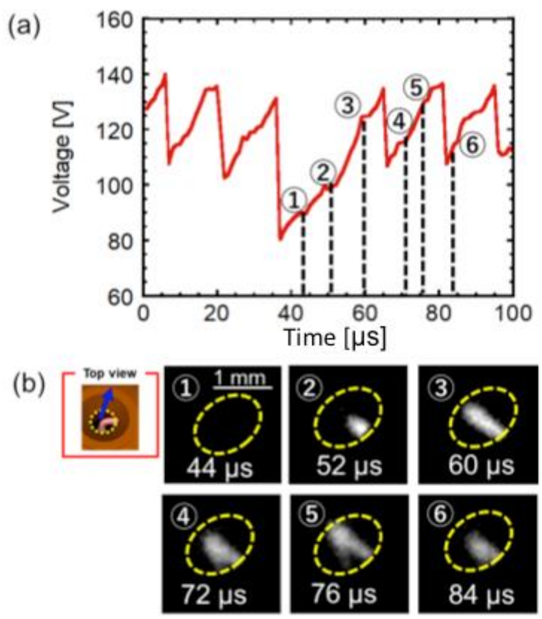

Fig.4. Representative arc voltage waveform (a) and corresponding high-speed snapshots of the arc at nozzle exit (b) at 9.5 A of arc current in the water plasma torch without mist generation.

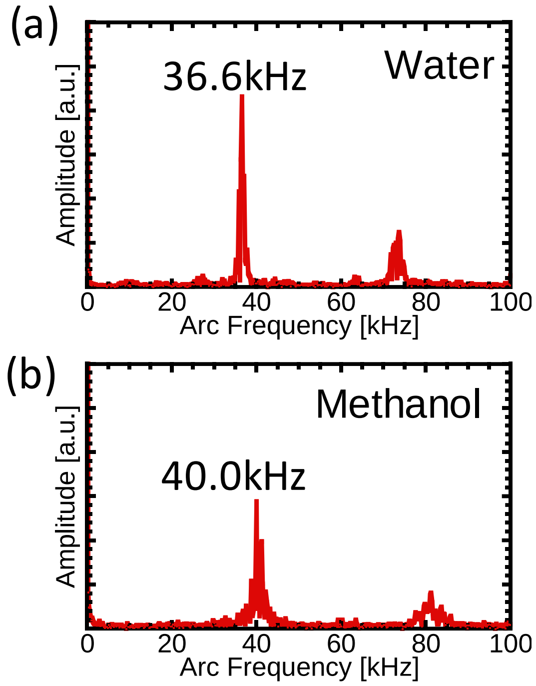

Fig.5. Fast Fourier Transform spectrum of arc voltage in the water plasma torch with mist generation at 9.5 A of arc current; (a) pure water and (b) 5mol% methanol solution.

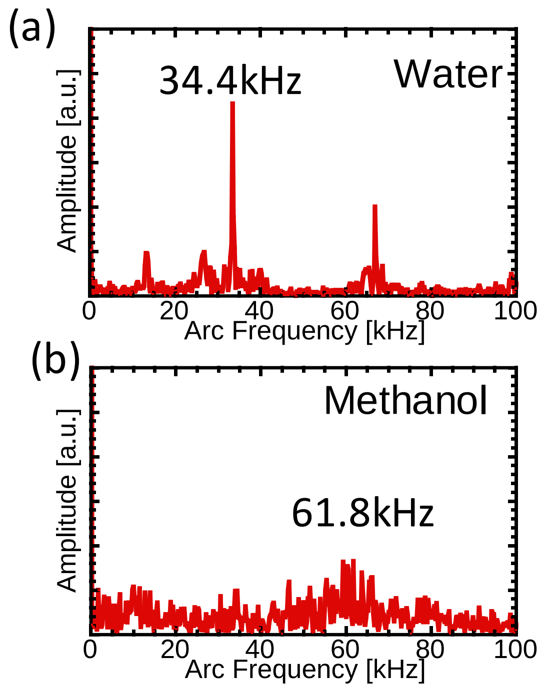

Fig.6. Fast Fourier Transform spectrum of arc voltage in the water plasma torch without mist generation at 9.5 A of arc current; (a) pure water and (b) 5mol% methanol solution.

torch without mist generation was lower than that in the torch with mist generation in Fig. 3(a).

Fast Fourier Transform (FFT) spectrum of the voltage waveform in the torch with mist generation is presented in **Fig. 5**. Sharp peaks at 36.6kHz in the water plasma and at 40.0kHz in the water plasma with methanol were clearly found. These results indicate that the arc fluctuation of the water plasma torch can be classified as a perfect restrike mode.

FFT spectrum of the voltage waveform in the water plasma torch without mist generation is presented in **Fig. 6**. Sharp peaks at 34.4kHz in the water plasma was clearly found. In addition, small peaks at around 20kHz and 40kHz were found. No sharp peaks in the water plasma with methanol are found. The arc instability in this plasma torch originate from the unstable water feeding by the stainless steel felt. Obtained results indicate that arc stability was improved by mist injection into discharge region. In particular, the stability improvement of the water plasma arc with methanol was significant. This result suggests that the water plasma torch with mist generation is promising torch for application to treatment of organic, emulsion and colloid solutions.

3-2. Effect of arc current on discharge characteristics

Effect of arc current on discharge characteristics in the water plasma torch with mist injection was investigated. **Figure 7** shows the effect of arc current on the frequency of the arc fluctuation. The arc frequency increases with the arc current due to larger Joule heating. Water evaporation is enhanced because of the larger Joule heating at higher arc current. Consequently, the larger gas flow rate leads to larger drag force at the nozzle, resulting in higher restrike frequency. In addition, the vapour pressure of methanol is higher than the vapour pressure of water. Therefore, mean frequency of water plasma arc with methanol is higher than that of water plasma arc.

The effect of arc current on the mean arc voltage is presented in **Fig. 8**. The electrical conductivity of arc is enhanced because of the larger Joule heating at higher arc current. Therefore, the mean arc voltage decreases as the arc current increases. In addition, the mean voltage of water plasma is higher than that of water plasma with methanol in the same arc current. Equilibrium compositions in water and methanol are shown in **Fig. 9**. Ionization degree in the case of methanol is higher than that in water case at the same temperature because ionization energy of C radical is relatively lower than O and H. Consequently, the electrical conductivity in methanol case becomes higher than that of water, resulting in lower arc voltage in methanol case.

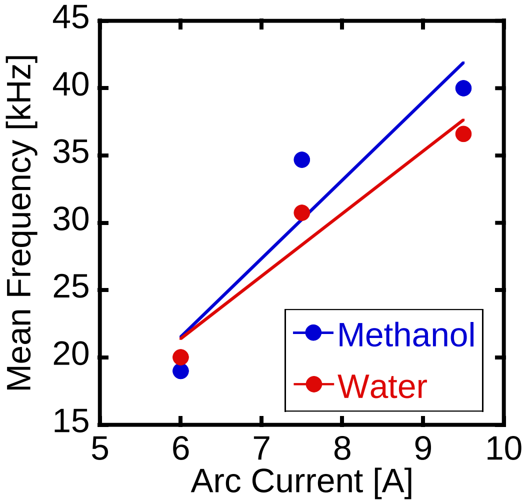

Fig.7. Effect of arc current on arc mean frequency.

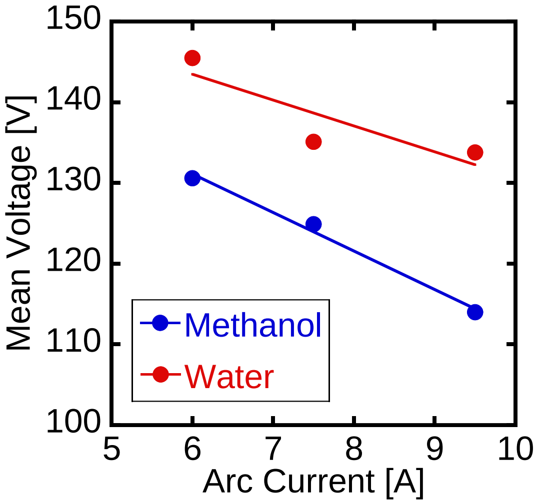

Fig.8. Effect of arc current on arc mean voltage.

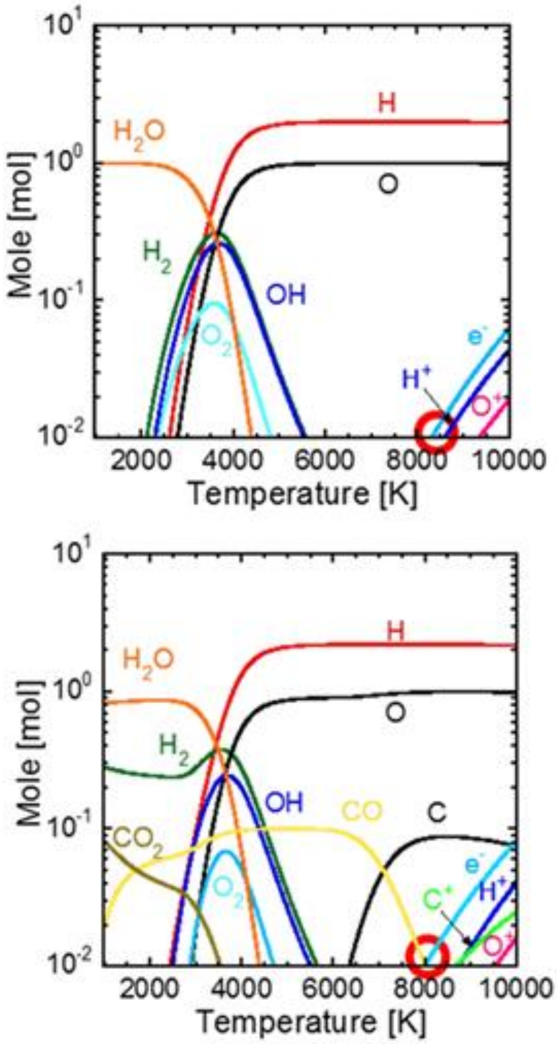

Fig.9. Equilibrium composition in different solutions; water (a) and 5mol% methanol (b).

4. Conclusion

Innovative water plasma torch with mist generation was developed. Stable continuous arc generation was achieved in the developed system. The high-speed camera observation synchronized with the voltage measurement was carried out to understand the fluctuation phenomena in the water plasma torch. periodical arc motion from the inside to outside of the anode nozzle was clearly observed in an axial direction in the water plasma torch. Then the arc voltage waveform has a periodic saw tooth shape because of a restrike phenomenon.

The arc frequency increases at higher arc current. The water plasma torch with mist generation is a promising thermal plasma generator for harmful waste decomposition and syngas generation system from the low-grade organic compounds.

5. References

[1] J. Heberlein, et al., Journal of Physics D, **43**, 2 (2010).

[2] H. Nishioka, et al, Thin Solid Films, **518** (3), 924-928 (2009).

[3] M. Yuan, et al., Environmental Science and Technology, **44**, 4710-4715 (2010).

[4] Y. Ozeki, et al., Journal of Fluid Science and Technology. **12** (3), JFST0022 (2017).