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Water Plasma Generation under Atmospheric Pressure for Waste Treatment

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DC 100%-steam plasma characteristics were investigated for the application of halogenated hydrocarbon decomposition, because steam plasmas are chemically reactive. Nevertheless, plasma system generally requires complex subsystems such as steam generator and cooling systems. The presented steam plasma system is portable light-weight plasma generation system that does not require gas-bomb. The system has high-energy efficiency resulting from the unnecessity of additional cooling water. High durability of the electrodes is strongly required for DC 100%-steam plasma, because the electrodes are exposed to reactive condition. Thus, electrode characteristics were investigated under different configurations and several conditions.

***Keywords*:** thermal plasma, steam plasma, waste treatment

1. Introduction

Thermal plasmas have distinctive advantages as following; high enthalpy to enhance reaction kinetics, high chemical reactivity, oxidation and reduction atmospheres in accordance with required chemical reactions, and rapid quenching to produce chemical non-equilibrium materials. Thermal plasma systems such as water-stabilized arc have been developed for high temperature source [1].

Steam plasmas are especially suitable for chemical processes for generation of reactive hydrogen and oxygen; halogenated hydrocarbons can be decomposed efficiently by hydrogen and oxygen. RF 100%-steam plasma performed high level destruction with ppm range concentration of destructed CFC or halon in the off-gas [2]. The small microwave plasma for CFC destruction has been used commercially [3].

DC plasma can be generated efficiently with simpler configuration than that of RF and microwave. DC argon plasma with injection of oxidizing gas such as steam and oxygen has already been operated [4]. DC steam plasma process is also applied to various waste treatments such as decomposition of PCB [5]. Nevertheless, electrode requires protection from erosion derived from high reactivity of steam plasma. Kim, et al. [5] used nitrogen or argon to protect tungsten cathode. Glocker, et al. [6] used hydrogen to protect thoriated tungsten cathode.

The plasma generation system generally requires complex sub-equipments such as gas-bomb or cooling system. Thus, efficient plasma generation systems have been required for the industrial application. The purpose of this paper is to generate steam plasma using DC portable light-weight system without additional cooling water and gas-bomb. The electrodes are exposed to severe condition of steam plasma without shield gas. Therefore, another purpose is to investigate electrode characteristics with the different configurations.

2. Thermodynamic Consideration

Chemical species have strong effect on durability of the electrode. Thermodynamic equilibrium was calculated by FACT in order to determine the species generated in plasma. FACT is database software for searching

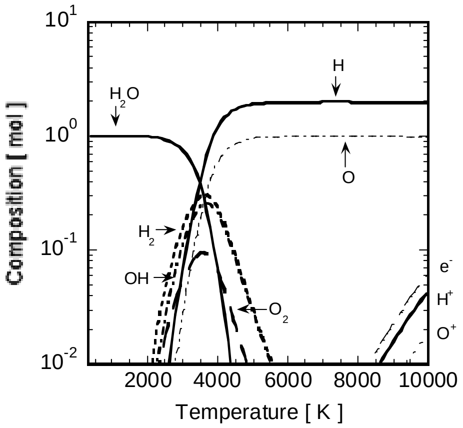

Fig. 1 Equilibrium diagram for water.

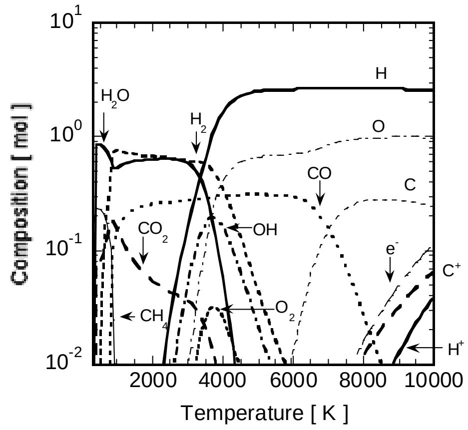

Fig. 2 Equilibrium diagram for the mixture of 15.5 mol%-ethanol and 84.5 mol%-water.

chemical equilibrium composition in which Gibbs free energy is the lowest.

Chemical composition of water is shown in **Fig. 1** as function of temperature. H_2O dissociates to O and H at 3500 K. Chemical composition of mixture of 15.5 mol%-ethanol and 84.5 mol%-water is shown in **Fig. 2**. Existence of CO results in reduction atmosphere. Reduction atmosphere would affect erosion of the electrode. C ionizes at lower temperature than O or H. Higher concentration of C^+ ion is attributed to smaller ionization energy; Ionization potential of C is 11.26 eV, beside that of H is 13.60 eV, and that of O is 13.62 eV. Low ionization potential of C leads to high conductance of plasmas with organic compounds.

3. Experimental Setup

The developed steam plasma torch is a DC thermal plasma generator of coaxial design with a cathode of hafnium embedded into the copper rod and a nozzle-type copper anode. When steam plasmas are applied to waste treatment, the use of additional steam generator is unsuitable, because the steam generator leads to larger and complicated system including the heating-up of the water feeding line preventing steam from condensation. The presented plasma torch can generate 100%-steam plasma without commercially available steam generator.

The configuration of DC steam plasma torch is presented in **Fig. 3**. The advantage of the presented steam plasma torch is generation of 100%-steam plasma by DC discharge. The features of the torch result from the simple steam generation; water from the water tank is heated up and evaporated at the anode region to form the plasma supporting gas. Simultaneously, anode is cooled by the water evaporation, therefore the electrode do not require additional water-cooling. The distinctive steam generation method leads to the portable light-weight plasma generation system that does not require the gas-bomb, as well as the high energy efficiency resulting from the unnecessity of the additional water-cooling. The energy efficiency was estimated to be 86 % from the measurement of the input power and the plasma enthalpy near the torch exit.

Fig. 4 is cross section of the cathode. Hafnium is embedded into the copper rod to work as the electron provider. Hafnium with the diameter of 0.5 mm, 1.0 mm or 2.0 mm was used to investigate the effect of the cathode configuration on the life-time and durability of the electrode.

Effect of plasma gas on the electrode

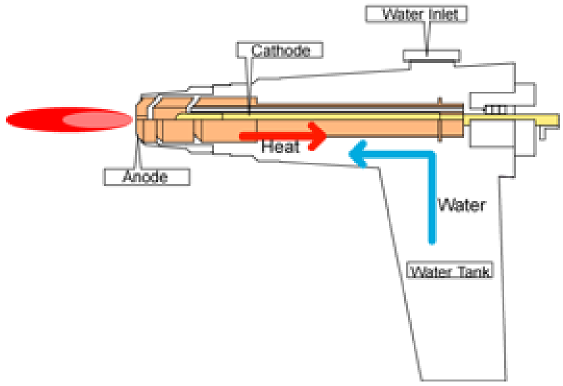

Fig. 3 Steam plasma torch with tank filled with water, methanol-water, ethanol-water.

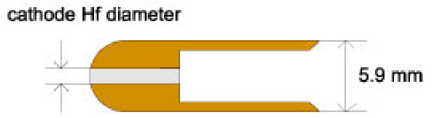

Fig. 4 Cross section of cathode with hafnium rod implemented in copper as electron provider.

life-time and characteristics of the plasmas was investigated for the comparison of different plasma gases. Therefore, the tank is filled with water, methanol-water (13.4 mol%-methanol and 86.6 mol%-water), or ethanol-water(15.5 mol%-ethanol and 84.5 mol%-water). Under the equilibrium condition, the composition prepared in liquid becomes equimolal in gas phase.

The steam plasma was generated under atmospheric pressure with the arc current at 6.4 A, and with the arc voltage at 120 V.

4. Results and Discussions

4-1. Effect of Cathode Diameter

Fig. 5-(a) shows the photographs of the unused cathodes of DC steam plasmas. **Fig. 5-(b)** shows the used cathodes of different hafnium diameters. The steam plasma generation was unstable after the long-time operation, then the arc was extinguished owing to the severe deformation of the cathode. These photographs were taken after the twice extinguishments of the steam plasma. The life-time shown below the photos is the elapse time.

The diameter of the hafnium cathode of 0.5 mm or 1.0 mm was strongly deformed, although the diameter of 2.0 mm retains the original shape. Smaller diameter of the hafnium cathode provides the localized arc root near the copper that surrounds the hafnium. Consequently, substantial amount of heat from the arc root to the surrounding copper results in the evaporation and deformation of the copper. In contrast, larger diameter of the hafnium cathode provides the uniform distributed arc root, preventing from the local heating of the copper.

Arc fluctuations due to periodic moving of the arc root on the electrodes have strong effects on the electrode life-time. We have investigated the existence of correlation between the voltage fluctuation and arc behavior. The correlation would be related to the electrode life-time. The voltage fluctuation, which is regarded as important parameter for the indication of the electrode life-time, was analyzed. We have evaluated the waveform and frequency estimated using Fast Fourier Transform, although these results are little related to the periodic electrode behavior. Therefore, the average and standard deviation of the voltage fluctuation are adopted as the indication for the arc behavior in this research.

The arc voltage was measured from 110 s after the arc ignition until 130 s; each measurement was performed during 20 s with

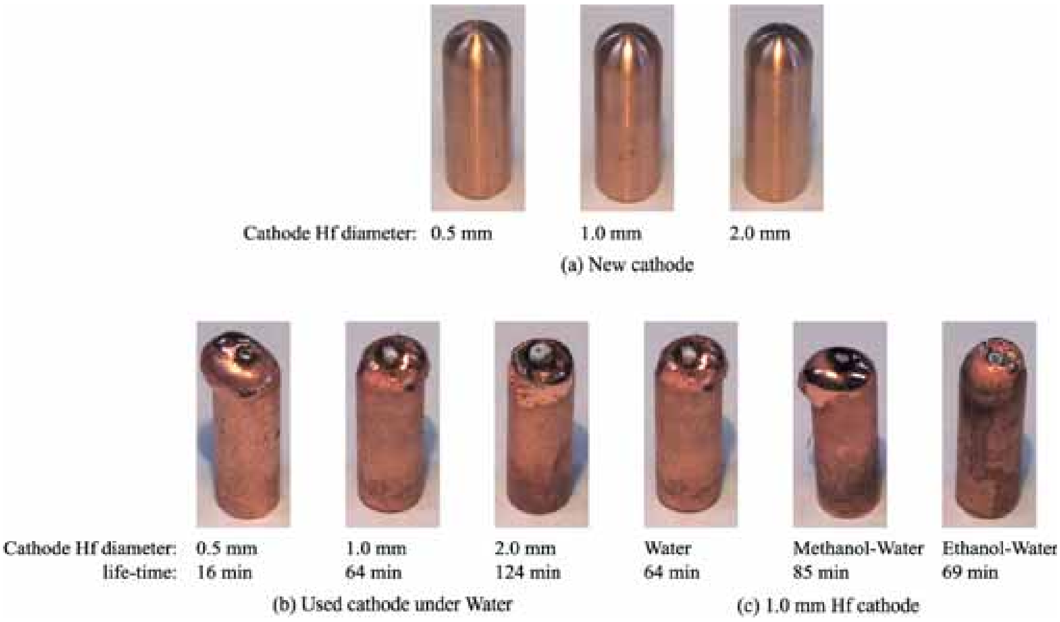

Fig. 5 Photographs of the new cathodes and used cathode

the sampling rate at 1 kHz.

The average of the arc voltage is shown in **Fig. 6** with the elapsed operation time for different diameters of hafnium cathode. For the hafnium diameter of 1 mm, the average arc voltage suddenly increases owing to the severe damage of the cathode.

The standard deviation of the arc voltage fluctuation is shown in **Fig. 7** with the elapsed operation time. The cathode diameter with 0.5 mm or 1.0 mm presents the sudden increase in the voltage standard deviation, indicating the severe damage of the cathode. The scattering of the standard deviation is wider with larger diameter of the hafnium cathode. This indicates that the arc root was distributed widely on the larger diameter hafnium, preventing from the intensive localized heating of the copper.

The weight loss of the cathode is shown in **Fig. 8** for different diameters of hafnium cathode. The copper surrounding the hafnium cathode is strongly evaporated in the case of the hafnium of 0.5 mm. The longest cathode life-time was obtained using the 2.0 mm diameter of hafnium.

The cathode durability can be correlated with the sudden increase in the standard deviation of the arc voltage fluctuation. More detailed examinations are required for determination of the optimum diameter of hafnium cathode for obtaining stable DC steam plasmas.

4-2. Comparison of Different Plasma Gases

Fig. 5-(c) shows the cathodes used with different plasma gases. The cathodes in the case of water and methanol-water are strongly deformed, while the shape of the cathode in the case of ethanol-water was retains the original shape. Hafnium oxide is observed on the cathode in the case of water, while hafnium was not oxidized in the case of methanol-water and ethanol-water. This indicates oxidation is suppressed by addition of organic compounds. As discussed in Sec. 2, organic compounds lead to reduction atmosphere. Therefore, stronger reduction atmosphere reduces the degree of cathode deformation.

The average of the arc voltage is shown in **Fig. 9** with the elapsed operation time for different plasma gases. The average arc

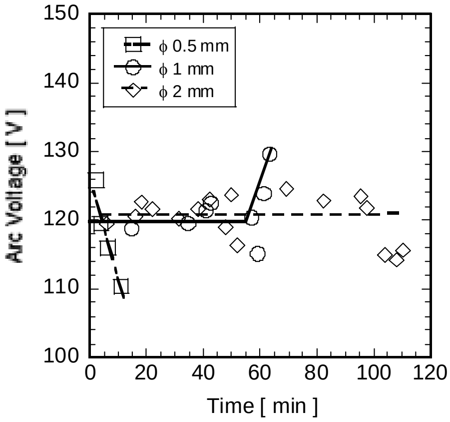

Fig. 6 Effect of Hf cathode diameter on mean arc voltage; plasma gas: water.

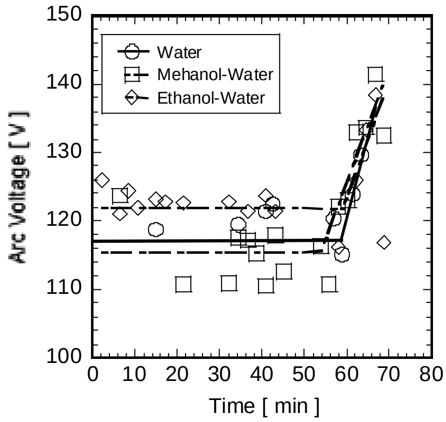

Fig. 9 Effect of plasma gas on standard deviation; Hf diameter: 1.0 mm.

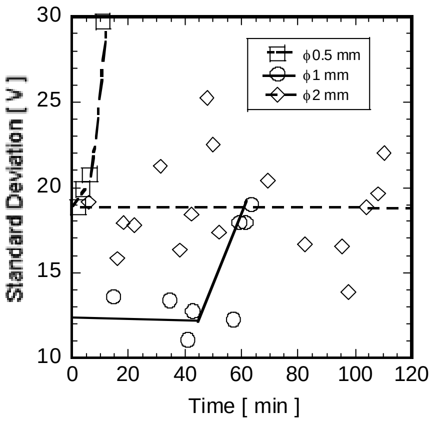

Fig. 7 Effect of Hf cathode diameter on standard deviation; plasma gas: water.

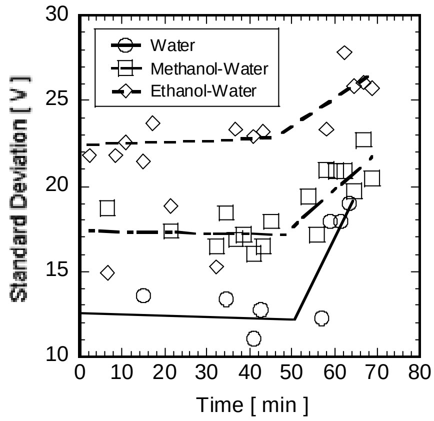

Fig. 10 Effect of plasma gas on standard deviation; Hf diameter: 1.0 mm.

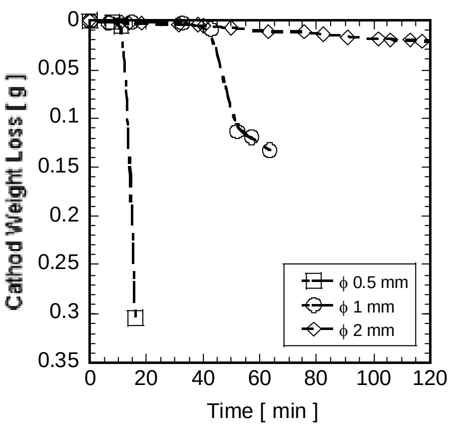

Fig. 8 Effect of Hf cathode diameter on cathode weight loss; plasma gas: water.

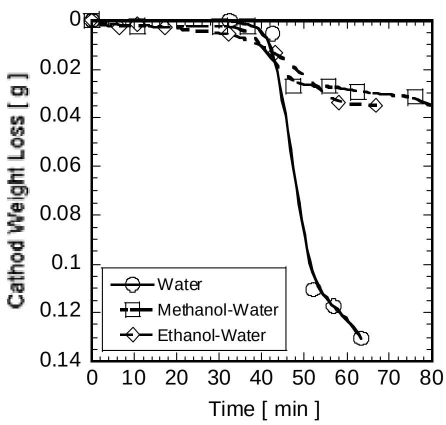

Fig. 11 Effect of plasma gas on cathode weight loss; Hf diameter: 1.0 mm.

voltages in each plasma gas suddenly increases owing to the severe damage of the cathode on the same time.

The standard deviations of the arc fluctuations are shown in **Fig. 10** with the elapsed operation time. The sudden increase in standard deviation is correlated to the cathode durability. The elapsed operation time until sudden increase in the standard deviation was almost the same. The standard deviations in the case of methanol-water and ethanol-water are larger than that of water. This indicates that the distribution of arc root in the case of methanol-water and ethanol-water is wider than that of water.

The weight loss of the cathode is shown in **Fig. 11**. The elapsed operation time until sudden weight loss of the cathode is almost the same. The largest weight loss of cathode is observed in the case of water. Weight loss of the cathode can be decreased by addition of organic compounds. The weight loss resulting from erosion can be reduced by stronger reduction atmosphere.

5. Conclusion

Stable DC 100%-steam plasma under atmospheric pressure was obtained. From the comparison of different diameters of the hafnium cathode, thinner diameter of hafnium strongly evaporated. From the comparison of different plasma gases, weight loss of the cathode can be suppressed by addition of organic compounds. The cathode durability can be correlated with the sudden increase in the standard deviation of the arc voltage fluctuation. More detailed examinations are required to optimize the plasma system.

Thermal plasmas would provide more capability for waste treatments, if thermal plasmas are utilized effectively as chemically reactive gas. The advantages of thermal plasmas, such as high enthalpy to enhance reaction kinetics, high chemical reactivity, oxidation and reduction atmospheres in accordance with required chemical reactions, and rapid quenching rate, should be utilized effectively for waste treatment.

Acknowledgement

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