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Water Plasma Generation Under Atmospheric Pressure for Waste Treatment

Takayuki Watanabe
Research·Laboratory for Nuclear Reactors
Tokyo Institute of Technology
2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550 JAPAN
Email: watanabe@nr.titech.ac.jp

DC 100%-steam plasma characteristics were investigated for the application of halogenated hydrocarbon decomposition because steam plasmas are chemically reactive. However, plasma system generally requires complex subsystems such as steam generators and cooling units. The presented steam plasma system is a portable light-weight plasma generation system that does not require any gas supply unit. The system has high-energy efficiency because it does not need additional cooling water. Electrodes of high durability are required for a DC 100%-steam plasma because the electrodes are exposed to reactive conditions. Thus, the electrode's characteristics were also investigated under different configurations and conditions.

Keywords: CFC decomposition, halon decomposition, steam plasma, thermal plasma, *and* waste treatment.

INTRODUCTION

Thermal plasmas have the following distinct advantages: 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 the water-stabilized arc, have been developed for high temperature sources (Hrabovsky 1998).

Steam plasmas are especially suitable for chemical processes for generation of reactive hydrogen and oxygen, which can decompose efficiently halogenated hydrocarbons. RF 100%-steam plasma performed high-level destruction with ppm range concentration of destructed CFC or halon in the off-gas (Takeuchi et al. 1995). The small microwave plasma for CFC destruction has been used commercially (Bessho et al. 2000).

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 (Murphy 2003). DC steam plasma process is also applied to various waste treatment methods such as decomposition of PCB (Kim et al. 2003, Watanabe and Shimbara 2003). Nevertheless, the electrode requires protection from erosion due to the high reactivity of steam

plasma. Kim et al. (2003) used nitrogen or argon to protect tungsten cathode. Glocker et al. (2000) used hydrogen to protect thoriated tungsten cathode.

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

THERMODYNAMIC CONSIDERATION

Chemical species have strong effect on the durability of an electrode. Thermodynamic equilibrium was calculated by FACT in order to determine the species generated in plasma. FACT is database software for searching chemical equilibrium composition in which Gibbs free energy is the lowest.

The chemical composition of water is shown in Figure 1 as function of temperature. H_2O dissociates to O and H at 3,500 K. Chemical composition of mixture of 15.5 mol%-ethanol and 84.5 mol%-water is shown in Figure 2. Existence of CO results in reduction atmosphere. Reduction atmosphere would affect the erosion of the electrode. C ionizes at a temperature lower than that for O or H. Higher concentration of C^+ ion is attributed to smaller ionization energy. The ionization potential of C is 11.26 eV, while that of H is 13.60 eV and that of O is 13.62 eV. The low ionization potential of C leads to the high conductance of plasmas with organic compounds.

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. Another steam generator will only lead to a larger and more complicated system that includes the heating-up of the water feeding line which prevents steam from condensation. The presented plasma torch can generate 100%-steam plasma without commercially available steam generator.

The configuration of the DC steam plasma torch is presented in Figure 3. The advantage of this steam plasma torch is that it generates 100%-steam plasma by DC discharge. The features of the torch result from simple steam generation: water from the water tank is heated up and evaporated at the anode region to form plasma-

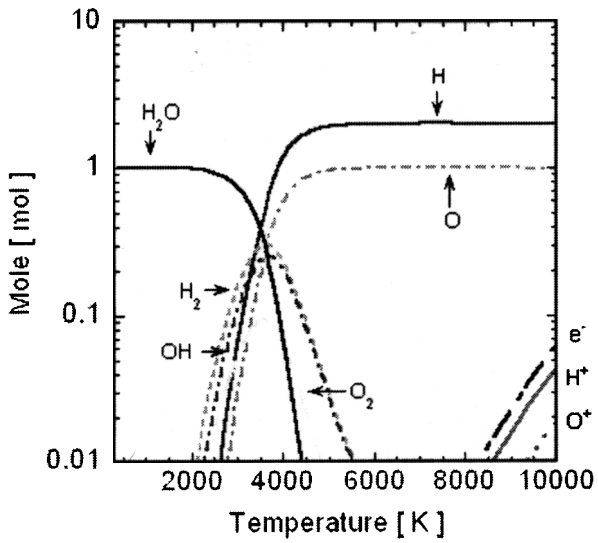


Figure 1. Equilibrium Composition of Water

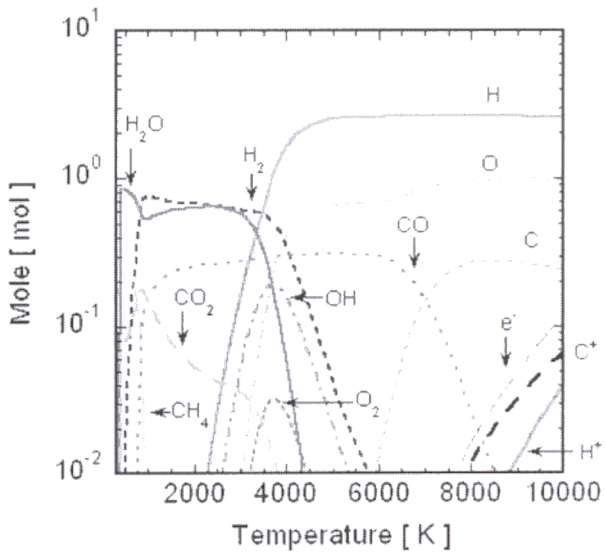


Figure 2. Equilibrium Composition of Mixture of 15.5 mol%-Ethanol and 84.5 mol%-Water

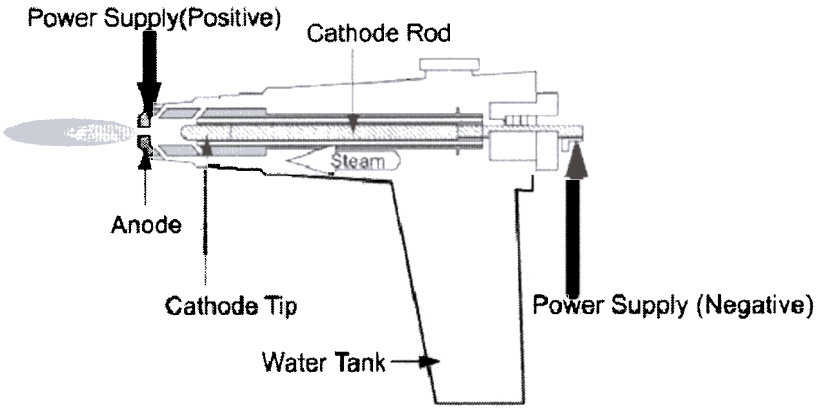


Figure 3. Steam Plasma Porch with Tank Filled with Water, Methanol-Water, or Ethanol-Water

supporting gas. Because, simultaneously, the anode is being cooled by the evaporation of water, the electrode does not require additional water-cooling.

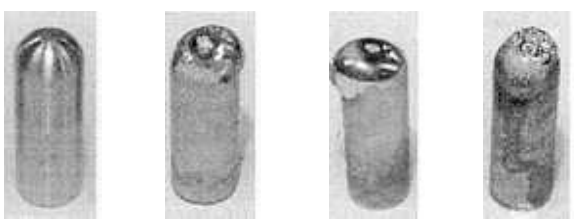
This particular steam generation method led to a portable light-weight plasma generation system that does not require gas supply units or additional water-cooling and, thus, has high energy efficiency. This energy efficiency was estimated at 86% from the measurement of the input power and the plasma enthalpy near the torch exit. In the cathode, hafnium was embedded into the copper rod to work as the electron provider. Hafnium with a diameter of 1.0 mm was used.

The effect of plasma gas on the electrode life-time and on the characteristics of plasmas were investigated for the comparison of different plasma gases. Therefore, the tank was 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 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 the arc voltage at 120 V.

RESULTS AND DISCUSSIONS

Figure 4 shows the cathodes used with different plasma gases. 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 two extinguishments of the steam plasma. The life-time shown below each photo is the elapsed time. The cathodes in the case of water and methanol-water were strongly deformed, while the cathode in the case of ethanol-water retained its original shape. Hafnium oxide was observed on the cathode in the case of water, however, hafnium was not oxidized in the case of methanol-water and ethanol-water. This observation indicates that oxidation is suppressed by the addition of organic compounds. As discussed in "Thermodynamic Consideration," organic compounds lead to reduction atmosphere. Therefore, stronger reduction atmosphere reduces the degree of cathode deformation.

Arc fluctuations due to periodic moving of the arc root on the electrodes have strong effects on the electrode life-time. Thus, the correlation between voltage fluctuation and arc behavior was likewise investigated. This correlation would be related to the electrode life-time. Voltage fluctuation, which is regarded as an important parameter for the indication of the electrode life-



New | Water 64 min | Methanol 85 min | Ethanol 69 min

Figure 4. Photographs of Cathodes with Different Plasma Gases

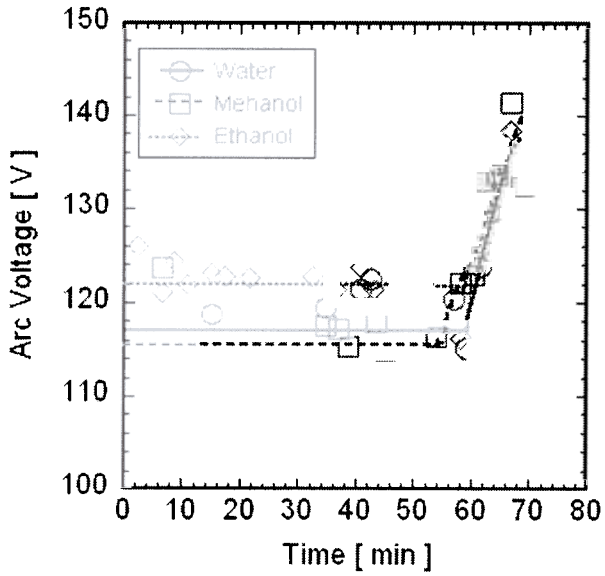


Figure 5. Effect of Plasma Gas on Mean Arc Voltage

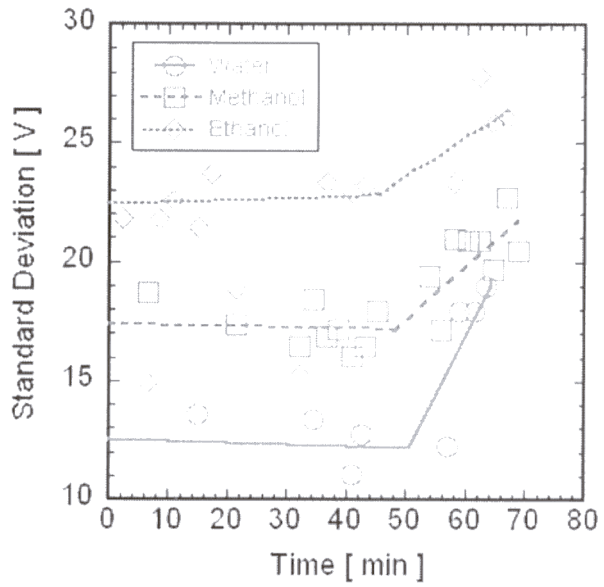


Figure 6. Effect of Plasma Gas on Standard Deviation

time, was also analyzed. Similarly, waveform and frequency, estimated using Fast Fourier Transform (FFT), were evaluated. The results, however, were not that related to periodic electrode behavior. Therefore, the average and standard deviations of voltage fluctuation were adopted as indications 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 the sampling rate at 1 kHz.

The average arc voltage is shown in Figure 5 with the elapsed operation time for the different plasma gases. The average arc voltage for each plasma gas was observed to suddenly increase owing to the severe damage of the cathode at about the same time.

The standard deviations of the arc fluctuations are shown in Figure 6 with the elapsed operation time. The sudden increase in standard deviation is correlated to the cathode durability. The elapsed operation time until the sudden increase in standard deviation was almost the same. The standard deviations in methanol-water and ethanol-water were 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 Figure 7. The elapsed operation time until sudden weight loss of the cathode was again almost the

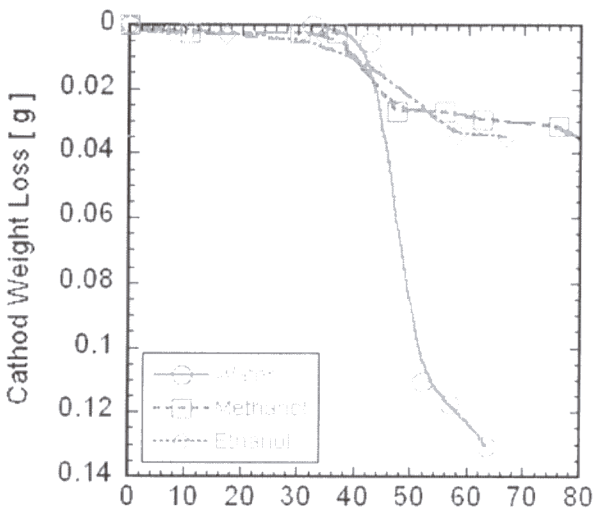


Figure 7. Effect of Plasma Gas on Cathode Weight Loss

same. The biggest weight loss of cathode was 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. The cathode durability can be correlated with the sudden increase in the standard deviation of the arc voltage fluctuation. More detailed examinations, however, are required to determine the optimum diameter of the hafnium cathode to obtain stable DC steam plasmas.

CONCLUSIONS

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 will provide more capability for waste treatment, 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.

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