DOI: 10.34343/ijpest.2021.15.e02006

Abatement of perfluorocarbons using direct current plasma generated in gas bubbles in water

Yuriko Matsuya, Ryota Miyazawa, Kei Ikeda, Nozomi Takeuchi, Koichi Yasuoka*

Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Japan

* Corresponding author: <u>vasuoka@hv.ee.e.titech.ac.jp</u> (Koichi Yasuoka)

Received: 29 March 2021 Revised: 28 May 2021 Accepted: 3 June 2021 Published online: 5 June 2021

Abstract

Reducing the use of perfluorocarbons (PFCs) in semiconductors and other industries is a key issue. To this end, to date combustion methods have often been implemented for large abatement systems. However, plasma could potentially be used to develop a compact system that operates at a low gas flow rate. Here, atmospheric direct current (DC) plasma generated in gas bubbles in water was demonstrated to remove C_2F_6 and CF_4 . Using nitrogen-based 1% C_2F_6 a removal rate of 90.6% was achieved at 35 mA and 0.071 standard liters per minute (SLM). Fourier-transform infrared spectroscopy (FTIR) analysis indicated that the byproduct ratio of CF_4 to C_2F_6 was below 1%; thus, almost all CF_4 was decomposed by the DC plasma. The decomposition characteristics of CF_4 were studied by changing the base gas, such as nitrogen and argon. The gas temperatures in both plasmas were approximately the same. However, the argon-based plasma showed a higher mean electron energy (by approximately 2 eV) and a higher removal rate at the same plasma power. In conclusion, both thermal and impact collision processes occur during the decomposition of CF_4 . The difference in the removal rate was possibly caused by the metastable atoms and ions in the argon-based scrubbers.

Keywords: Abatement, tetrafluoromethane (CF_4), hexafluoroethane (C_2F_6), DC plasma, gas bubble.

1. Introduction

The primary approach for reducing perfluorocarbon (PFC) emissions from industries is to develop efficient and inexpensive abatement equipment. The methods of PFC abatement that are currently applied in practical settings involve combustion [1], hydrolysis using catalysts [2] and plasma processes. In combustion systems, the temperatures corresponding to the decomposition of typical PFCs, such as CF₄, C₂F₆, SF₆, and NF₃ are 1600 °C, 900 °C, 1000 °C, and 800 °C, respectively [1]. Further, these combustion systems do not only require a sufficiently high temperature for PFC decomposition, but also require H and O atoms for the fixation of the dissociated F and the stabilization of the associated reactions. Thus, the recombination of the dissociated C and F atoms is prevented, and as such, the abatement process consists of two stages, PFC decomposition and the recovery of fluorine atoms in water. The equipment used to realize combustion-based PFC abatement is suitable for a large amount of PFCs as well as large flow-rate gas processes.

Conversely, PFC abatement via plasma processes is advantageous for small flow-rate gas processes and offers the possibility to reduce the initial and running cost. The plasma processes include inductively-coupled plasma [3], dielectric barrier plasma [4], microwave plasma torch [5, 6], and nitrogen thermal plasma [7]. Plasma abatement systems are compact and have lower gas flow rates than other systems, which make them suitable for installation in laboratories and small plants. The complete removal of CF₄ can be achieved with low-pressure plasma [3], but this approach requires the installation of a vacuum pumping system, and this increases device size as well as initial cost. However, atmospheric nonthermal plasmas do not require vacuum systems and have been used to achieve CF₄ removal rates up to 56% based on the dielectric barrier plasma process [4], and 95% [5, 6], and 99.6% [7] based on the use of plasma torch devices. Unfortunately, these systems require large gas scrubbers that supply water showers to prevent recombination between dissociated

C and F atoms. Additionally, plasma-based PFC decomposition processes were evaluated taking plasma temperature into account, while ignoring the energetic particles in the plasma.

Plasmas generated in gas bubbles in water have shown high decomposition efficiencies with respect to a highly concentrated acetic acid solution [8, 9] and perfluoro compounds in perfluorooctanoic or perfluorooctanesulfonic acid [10, 11]. In this study, we investigated plasma-based PFC abatement using a plasma that can supply sufficient H and O atoms and capture dissociated F at the gas-liquid boundary. C_2F_6 and CF_4 were decomposed using atmospheric-pressure DC plasma generated within gas bubbles in water. Further, nitrogen- and argon-based plasma processes were compared to evaluate the effect of gas temperature and the energetic species in plasma on the abatement performance.

2. Experimental and measurement apparatus

Fig. 1 shows a schematic of the abatement reactor featured in this study, which used DC plasma and diagnostic equipment. Tap water (50 mL) was filled into the reactor, which was an acrylic container with a height of 110 mm and a square cross section of 36 mm \times 36 mm. A ceramic plate of 0.3 mm in thickness separated the water and gas. Mixture gases of nitrogen-based 1% C₂F₆, 1% CF₄, and argon-based 1% CF₄ flowed through the 0.3 mm hole of the ceramic plate. The flow rate was controlled using a mass flow controller (Kofloc, model3200) with an adjustable flow rate of up to 0.1 standard liters per minute (SLM). A high-voltage (HV) electrode, made from a tungsten wire with thickness 0.2 mm, was mounted below the hole on the ceramic plate. Given that this HV electrode undergoes corrosion, a 0.4-mm tungsten wire was used to perform experiments involving a higher current magnitude. Further, the metal terminal was placed in water, which served as the ground electrode.

A regulated HV DC source (Matsusada Precision, HAR30R40) was used to supply a voltage across the HV electrode through a 200-k Ω ballast resistor (Japan Finechem, RH12HVPS, five resistors connected in parallel). This was done to stabilize the discharge current up to 20 mA. A 100-k Ω resistor (Japan Finechem, RH150HVP, two resistors connected in parallel) was used to stabilize the discharge current above 20 mA. A resistor (1 k Ω) was inserted into the HV circuit to monitor the current. The picture on the right-hand side of Fig. 1 shows typical CF₄/N₂ plasma generated between the HV electrode and the inner boundary of a gas bubble. The height of this bubble was approximately 5 mm, which however, changed with time as the flow rate changed.

Ion concentrations of F^- , NO_2^- , and NO_3^- in the water were measured using an ion chromatography (Metrohm, 861 Advanced Compact IC). HCN concentration in the exhaust gas was evaluated using a gas detector tube (Gastec, 12L, 0.5–150 ppm). The byproduct species in the exhaust gas were analyzed via FTIR (Horiba, FG110A) using a gas cell with an optical length of 10 cm.



Fig. 1. Schematic diagram of abatement reactor, diagnostics, and plasma generated within gas bubble in water; FTIR = Fourier-transform infrared spectroscopy.

Optical emissions from the plasma were measured using spectrographs through a quartz window mounted on the side wall of the reactor. The visible light emissions from nitrogen- and argon-based plasmas were detected using a fiber-optic spectrometer (Ocean Optics USB4000, 200–850 nm). The nitrogen second-positive band (360–385 nm) in the nitrogen-based plasma was measured using another spectrometer (Ocean Optics USB4000, 275–395 nm), and the OH spectrum in the argon-based plasma was measured using a monochromator spectrograph with a wavelength resolution of 0.06 nm (Solar TII, MS3504I).

The gas temperature was estimated to be equivalent to the rotational temperature. Specifically, the rotational and vibrational temperatures corresponding to the nitrogen-based plasma were determined by fitting the calculated spectrum to the experimentally obtained second-positive spectra. The OH emission spectrum, which was determined using LIFBASE, was fitted to the experimental one to determine the rotational temperature corresponding to the argon-based plasma. The mean electron energy versus input power for each gas was calculated using the Boltzmann simulation code: BOLSIG+ [12].

The PFC removal rate was defined as shown in Eq. (1). F_{Water} is the molar amount of fluorine (F) in the water; it was calculated by multiplying the F ion density in the water and the water volume. F_{PFC} is the accumulated molar amount of F in the input PFC gas during each plasma treatment. The removal efficiency was defined as shown in Eq. (2), where m_{PFC} and W are the amount of PFC and energy consumption in the reactor, respectively. The energy, W, could be calculated as a product of the discharge current, the voltage between the HV electrode and the ground electrode, and the treatment time. Thus, the energy consumed included power dissipation in water.

$$\eta_{\text{removal}}(\%) = \frac{F_{\text{Water}}}{F_{\text{PFC}}} \times 100 \tag{1}$$

$$\eta_{\text{efficiency}} = \frac{m_{\text{PFC}}[g]}{W[kWh]}$$
(2)

3. Results and discussion

3.1 Removal of C₂F₆

Fig. 2 (a) and (b) shows the voltage and current waveforms immediately after the start: (a) and 10 min after operation: (b) under the conditions of nitrogen-based 1% C₂F₆, 0.1 SLM and with a 10 mA current. The voltage waveforms fluctuated at an interval of 15 ms according to the expansion and shrinkage of the bubbles in water. Further, the voltage values were low when the bubble shrank owing to the shortness of the plasma length, and the waveform included a voltage drop with water; thus, the average voltage decreased by approximately 200 V as shown in Fig. 2 (b) owing to the increasing conductivity of water.



Fig. 2. Voltage and current waveforms immediately after the start (a) and after 10 min (b) with a 0.1 SLM flow of $1\% C_2F_6$.

Fig. 3 shows the C_2F_6 removal rates defined by Eq. (1) after 2 min of treatment at a gas flow rate of 0.1 SLM. The removal rate increased to 79.9% when the discharge current increased from 10 mA to 35 mA. Fig.

4 shows the removal rate and removal efficiency as a function of the gas flow rate from 0.06 to 0.1 SLM within 2 min of treatment under a current of 35 mA. Specifically, at 0.071 SLM, the removal rate was 90.6%. Additionally, no clear dependence of the removal rate on the gas flow rate was observed; however, the removal efficiency increased with increasing flow rate, and at a lower gas flow rate, the amount of C_2F_6 seemed to be insufficient with respect to the decomposing capacity of the plasma.



Fig. 3. C_2F_6 removal rate versus discharge current for 2-min treatment at a gas flow rate of 0.1 SLM.



Fig. 4. C_2F_6 removal rate on the left axis and removal efficiency on the right axis as a function of flow rate; current = 35 mA.

The FTIR spectra (Fig. 5) show the changes in the peak values for gas species before and after the 10 min, 35 mA plasma abatement of C_2F_6 . The negative values of CO_2 were caused by noise in the measurement box. The main peak at 1250 cm⁻¹ for C_2F_6 exceeded the measurement range; therefore, the second peak at 1115 cm⁻¹ for C_2F_6 was used for the evaluation. After the plasma abatement, the second peak corresponding to C_2F_6 decreased from 2.1 to 0.30 [a.u.]. The removal rate of C_2F_6 was calculated to be 86% from the reduction in the second peaks; this is approximately consistent with the values obtained by ion chromatography. The byproducts, such as CF_4 , NO_2 , CO, CO_2 , H_2O , and a small amount of HCN, were detected. The magnified spectra of CO and CN are shown in the inset in Fig. 5. Less CF_4 was generated than C_2F_6 ; thus, the collection efficiency of F with plasma generated in water bubbles appeared to be quite high because of the direct interaction between plasma and water.

The HCN concentration measured using the gas detector tube was 28 ppm after 5 min of treatment under a current of 35 mA. This value decreased to 8 ppm when the exhaust gas was bubbled into water at 5°C, in which HCN dissolved.



Fig. 5. FTIR spectra illustrating the detected gas species before abatement in black and after abatement in red at a current of 35 mA for 10 min. The red circle shows the second C_2F_6 peak before abatement.

3.2 Removal of CF₄

Nitrogen and argon-based 1% CF₄ gases were used for the abatement of CF₄. Pictures of the plasma generated in each gas bubble are shown in Fig. 6 (a): nitrogen and (b): argon. The experimental conditions were an average current of 10 mA, a gas flow rate of 0.071 SLM, an exposure time of 1/20 s, and an iris of F7.5.

The optical emission spectra of the nitrogen-based (pink) and argon-based (black) 1% CF_4 bubbles are shown in Fig. 7, which clearly shows spectra corresponding to OH, CN, and C₂ in the argon-based plasma.



Fig. 6. Plasma pictures in nitrogen-based (a) and argon-based (b) 1% CF₄ bubbles. The average plasma current was 10 mA at a flow rate of 0.071 SLM.



Fig. 7. Emission spectra of nitrogen-based (pink) and argon-based (black) 1% CF₄ bubbles. The average plasma current was 10 mA at a flow rate of 0.071 SLM.



Fig. 8. Voltage and current waveforms of nitrogen-based CF₄ plasma (a) and argon-based 1% CF₄ plasma (b) at a flow rate of 0.071 SLM.

The voltage and current waveforms of nitrogen-based 1% CF₄ plasma are shown in Fig. 8 (a). The fluctuating waveforms at 15 ms intervals were caused by the generation and collapse of bubbles in water, as seen in the C_2F_6 abatement. The sustaining voltage, which included the voltage drop with water, was approximately 1.2 kV on average. Fig. 8 (b) shows the current and voltage waveforms of argon-based plasma. The sustaining voltage was approximately 600 V, which was approximately half that the nitrogen-based plasma. Possibly, there are two reasons why the sustaining voltage for the argon plasma was low: the low values of the

cathode fall voltage and the electric field in the positive column of the argon plasma compared with the nitrogen plasma [13, 14]. However, the characteristics of the plasma generated between the metal electrode and water surface are still unclear and might be different from those observed when the plasma has no gas-water boundaries [15].

The ion concentrations of F^- , NO_2^- , and NO_3^- were detected in water after a treatment with nitrogen-based 1% CF₄ at 10 mA and 0.071 SLM. The amounts of ion species increased with time, as shown in Fig. 9. The NO_2^- concentration increased from 4.9 to 7.2 mg L⁻¹ with increasing flow rate (from 0.036 to 0.143 SLM) after 2min treatment at 10 mA. However, the NO_3^- concentration was 5.8 mg L⁻¹, which was almost independent of the flow rate. NO_2 was produced in the gas phase; therefore, its concentration increased with increasing flow rate. NO_2 dissolved into the water and formed NO_2^- ; thus, the concentration of NO_2^- was proportional to the flow rate. The formation process of NO_3 might have been limited in water; thus, OH or other oxidation substances may have limited the formation of NO_3^- . The conductivity of the solution increased with increasing ion concentration. The initial conductivity (161 μ S cm⁻¹) increased to 1.63 mS cm⁻¹after 60 min of treatment, and the pH changed from 7.5 to 2.4. further, the CF₄ removal rate decreased slightly from 7.0% at 10 min to 5.9% at 60 min with the nitrogen-based 1% CF₄ at 10 mA and 0.071 SLM. Therefore, it appeared that conductivity, ion species, pH, and solution temperature affect the abatement processes.



Fig. 9. Detected ion species in water after treatment of nitrogen-based 1% CF_4 under the conditions of a 10 mA current and a flow rate of 0. 071 SLM.



Fig. 11. Gas temperature for nitrogen- and argonbased plasma versus input power at a flowrate of 0. 1 SLM.



Fig. 10. Comparison of CF₄ removal rate versus input power for 2-min treatment at different gas flow rates.



Fig. 12. Mean electron energy versus input power obtained by BOLSIG+.

Fig. 10 shows the removal rates of CF_4 in argon and nitrogen as a function of the average power (the plasma current was regulated at 5 and 10 mA). The gas flow rates of nitrogen plasma were 0.071 and 0.14 SLM and those of argon plasma were 0.10 and 0.20 SLM. The removal rate was calculated after 5 min of treatment. A higher removal rate was obtained at lower flow rates in both cases. However, comparing the removal rates at

the same input power revealed that the removal rate obtained with argon was higher than that obtained with nitrogen.

FTIR analysis of the exhaust gas detected CO and CO₂. However, the NO₂ concentration was low owing to its high solubility in water. Fluorine compounds other than CF₄ were not detected. It appears that fluorine substances other than CF₄ were completely trapped through the plasma–water interaction. There are two possible abatement processes of CF₄: thermal dissociation or the impacts of electrons, ions, and metastable atoms. The gas temperature and mean electron energy in both cases were studied to determine why the removal rate was higher when using argon-based plasma.

Fig. 11 shows the calculated gas temperatures as a function of the average input power using the spectroscopic method as described in section 2. The input power was varied by changing the current in the range of 5–40 mA at a flowrate of 0.1 SLM. The gas temperature increased with increasing input power. However, approximately the same gas temperature was obtained for each gas.

For the simulation of mean electron energy, the gas species used were nitrogen- and argon-based, with 1% CF₄ and 3% H₂O [16]. The simulation was conducted at a reduced electric field of 126 Td (1 Td = 1×10^{-17} Vcm²) and a gas temperature of 3000 K for nitrogen-based plasma. In the case of argon-based plasma, a reduced electric field of 55 Td and a gas temperature of 2000 K were used. The electron energy distribution function (EEDF) of nitrogen-based plasma had two peaks at 1.7 eV and 6.3 eV; its tail extended to 20 eV. This distribution can be explained by the fact that the electrons with energies of several eV were consumed by the vibrational excitation of nitrogen. The EEDF of the argon-based plasma had one peak at 7 eV and its tail extended to 20 eV. As shown in Fig. 12, the mean electron energy of the argon-based plasma was approximately 2 eV higher than that of the nitrogen-based plasma at the same input power. This may have been caused by energy consumption in the vibrational excitation of the nitrogen based plasma at the argon-based plasma treatment.

Thermal decomposition is an established process in industrial applications. Therefore, determining how the thermal equilibrium state varies with respect to temperature is important for understanding the abatement process of CF₄. The software MALT [17] was used to calculate the equilibrium composition for nitrogen- and argon-based plasmas. The molar fractions are shown in the left-hand plot of Fig. 13 (a) and (b) for 1% CF₄, 1% H₂O, and 98% N₂. CF₄ started to decompose at 600 K and was completely decomposed at 2300 K. Nitrogen atoms appeared at temperatures above 3500 K. As shown in Fig. 11, the gas temperature of the nitrogen-based plasma exceeded 2000 K. Almost all CF₄ should decompose at this temperature according to the thermal equilibrium state. However, the removal rate in the experiment was below 5% (Fig. 10). This discrepancy between the experimental data and the MALT calculations may have been cause by the non-equilibrium state of the plasma and the quick recombination of dissociated species.



Fig. 13. Molar fractions of compositional substances versus temperature for nitrogen-based plasma (a) and argon-based plasma (b) obtained by MALT.

In the case involving a lower H₂O concentration, such as 1% CF₄, 0.1% H₂O, and 98.9% N₂, CF₄ decomposed slightly at temperatures below 2000 K, but fully at 2700 K. Additionally, at temperatures above 2000 K, the byproducts, CF₂, CF, and CN were generated; however, CO₂, COF₂, and CO, which were observed as shown in Fig. 13 (a), were not generated. This difference was possibly caused by the dissociated O atoms

from H_2O . The decomposition temperature of CF_4 was 2700 K, while that at 1% H_2O was 2300 K. Thus, the H_2O in bubbles not only capture the dissociated fluorine, but also accelerate CF_4 decomposition.

Fig. 13 (b) was calculated under the conditions of 1% CF₄, 1% H₂O, and 98% Ar. The composition was almost the same as for the nitrogen-based plasma. The reason for the absence of any dependence on the base gas was probably because nitrogen molecules were not decomposed by heat until the temperature reached 3500 K. Thus, the thermal process of CF₄ decomposition cannot adequately explain the high removal rate for the argon-based plasma.

The high-energy electrons collided with nitrogen and H₂O molecules and generated N and OH radicals, as follows: $N_2 + e \rightarrow N \cdot + N \cdot + e$ and $H_2O + e \rightarrow OH + H \cdot + e$. However, the rate constants of the reactions of CF₄ with O, H, N, and OH radicals are extremely small [18, 19]. Thus, the primary processes are thermal decomposition and impact dissociation by electrons, ions, and metastable atoms. The gas temperature of the argon-based plasma was 1500 K or higher, as shown in Fig. 11. Therefore, parts of the CF₄ molecules can be decomposed to form CO₂, CO, and HF by the thermal process. In addition, the electron energy, which was noted in the EEDF calculation, was high enough to decompose CF₄ by the following impact processes:

 $CF_4 + e \rightarrow CF_3 + F^-$, $CF_4 + e \rightarrow CF_3 + F + e$, $CF_4 + e \rightarrow CF_2 + 2F + e$, $CF_4 + e \rightarrow CF + 3F + e$

As a result, both the thermal and impact processes occurred during the decomposition of CF₄ in the DC plasma generated in the bubble. The argon-based plasma showed a higher removal rate, and higher electron energy than the nitrogen-based plasma. Therefore, the higher mean electron energy and the metastable argon atoms (Ar⁺) and ions (Ar⁺) may have accelerated the decomposition of CF₄ by the argon-based plasma.

4. Conclusion

The abatement of PFCs was demonstrated using atmospheric-pressure DC plasma within gas bubbles in water. Nitrogen-based 1% C_2F_6 gas was abated, and a removal rate of 90.6% was achieved under the conditions of 35mA and 0.071 SLM. FTIR analyses indicated the generation of byproducts such as CF_4 , CO, CO_2 , NO_2 , and HCN in the exhaust gas. The ratio of CF_4 to C_2F_6 was below 1%; thus, almost all CF_4 was decomposed by the plasma.

 CF_4 , which was more persistent than C_2F_6 , was decomposed using nitrogen-based and argon-based 1% CF_4 plasmas. The gas temperature and mean electron energy were estimated by optical analyses, and the thermal equilibrium state was calculated for different temperatures. The gas temperature increased from 1500 K to 3500 K with increasing input power. The gas temperatures of both gases were approximately the same. The EEDF of nitrogen-based plasma had two peaks at 1.7 eV and 6.3 eV whereas the argon-based plasma had one peak at 7 eV. The mean electron energy of the argon-based plasma was approximately 2 eV, which was higher than that of the nitrogen-based plasma at the same input power. In conclusion, both thermal and impact collision processes occurred during the decomposition of CF_4 . However, the argon-based plasma had a higher mean electron energy and contained metastable atoms and ions, which could explain its higher removal rate of CF_4 .

References

- [1] Shibuya K., Kobayashi Y., and Watanabe N., Combustion abatement technology for perfluoro compounds reduction, *J. Vac. Soc. Jpn.*, Vol. 52 (7), pp. 388–392, 2009. (in Japanese)
- [2] Hitachi, Ltd., Catalytic PFCs decomposition system, J. Vac. Soc. Jpn., Vol. 52 (7), pp. 403-406, 2009.
- [3] Kuroki T., Mine J., Odahara S., Okubo M., Yamamoto T., and Saeki N., CF₄ decomposition of flue gas from semiconductor process using inductively coupled plasma, *IEEE Trans. Ind. Appl.*, Vol. 41, pp. 221–228, 2005.
- [4] Kim Y., Kim K., Cha M. S., Song Y., and Kim S. J., CF₄ decompositions using streamer- and glow-mode in dielectric barrier discharges, *IEEE Trans. Plasma Sci.*, Vol. 33 (3), pp. 1041–1046, 2005.
- [5] Hong Y. C., and Uhm H. S., Abatement of CF4 by atmospheric–pressure microwave plasma torch, *Phys. Plasmas*, Vol. 10 (8), pp. 3410–3414, 2003.
- [6] Mangyou H., Watanabe N., Hattori K., Watanabe T., Sugimori Y., Shibuya K., and Hasaka S., High performance atmospheric plasma abatement system for PFC reduction, *IEEE Inter. Sympo. Semicond. Manuf. 2005 (ISSM 2005)*,

DOI: 10.1109/ISSM.2005.1513352, 2005.

- [7] Choi S., Hong S. H., Lee H. S., and Watanabe T., A comparative study of air and nitrogen thermal plasmas for PFCs decomposition, *Chem. Eng. J.*, pp. 193–200, 2012.
- [8] Takeuchi N. and Yasuoka K., Review of plasma-based water treatment technologies for the decomposition of persistent organic compounds, *Jpn. J. Appl. Phys.*, Vol. 60, pp. SA0801 (13 pages), 2021.
- [9] Takahashi K., Kawamura S., Yagi I., Akiyama1 M., Takaki K., and Satta N., Influence of reactor geometry and electric parameters on wastewater treatment using discharge inside a bubble, *Int. J. Plasma Environ. Sci. Technol.*, Vol. 13 (2), pp. 74–82, 2019.
- [10] Obo H., Takeuchi N., and Yasuoka K., Decomposition of perfluorooctanoic acid in water using multiple plasma generation, *IEEE Trans. Plasma Sci.*, Vol. 41 (12), pp. 3634–3639, 2013.
- [11] Takeuchi N., Suzuki D., Okada K., Oishi K., Kodama S., Namihira T., and Wang D., Discharge conditions for efficient and rapid decomposition of perfluorooctane sulfonic acid (PFOS) in water using plasma, *Int. J. Plasma Environ. Sci. Technol*, Vol. 14 (2), pp. e02006 (12pp), 2020.
- [12] BOLSIG+: http://www.bolsig.laplace.univ-tlse.fr/.
- [13] Raizer Y. P., Gas Discharge Physics, Springer: Berlin, Germany, 1991.
- [14] Dyatko, N. A., Ionikh Y. Z., and Napartovich A. P., Influence of nitrogen admixture on plasma characteristics in a dc argon glow discharge and in afterglow gas discharge physics, *Atoms*, Vol.7 (13), pp. atoms7010013, 2019.
- [15] Ikeda K., Takeuchi N., and Yasuoka K., Experimental and modeling investigation of atmospheric DC argon plasma having a liquid electrode, 40th IOP Conf. Plasma Physics, 2013.
- [16] Takeuchi N., Ishii Y., and Yasuoka K., Modelling chemical reactions in dc plasma inside oxygen bubbles in water, *Plasma Sources Sci. Technol.*, Vol. 21, pp. 015006, 2012.
- [17] MALT: http://www.kagaku.com/malt/product_jp.html
- [18] Chang M. B., and Chang J-S., Abatement of PFCs from semiconductor manufacturing processes by nonthermal plasma technologies: A critical review, *Ind. Eng. Chem. Res.*, Vol. 45, pp. 4101–4109, 2006.
- [19] Chen H. L., Lee H., Cheng L. C., Chang M. B., Yu S. J., and Li S., Influence of nonthermal plasma reactor type on CF₄ and SF₆ abatements, *IEEE Trans. Plasma Sci.*, Vol. 36 (2), pp. 509–515, 2008.