



Optical Emission Spectroscopy in Cooking Exhaust from a Wet Scrubber/Atmospheric Plasma Reactor

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ABSTRACT

This study introduced a self-developed wet scrubber/plasma reactor (WSB/PR) system to treat cooking fumes, and measured the changes in the optical emissions spectra (OES), before and after treatment using OES, in order to understand the changes of OES in a gaseous phase from waste gas. In terms of operational parameters of the experiment, the scrubbing solution used in WSB was tap water and an enzyme scrubbing solution, and atmospheric pressure plasma was applied inside PR. Furthermore, five different output powers (0.112 kJ/m³, 0.129 kJ/m³, 0.138 kJ/m³, 0.146 kJ/m³, and 0.156 kJ/m³) were utilized to conduct experiments. The experimental results showed that, through the operations of five different plasma output powers, active species C, C₂, CH, N, H γ , N₂, N₂⁺, NO, C⁺, NH, O₂⁺, H₂, and O can be tested under the following three situations: (i) start PR (plasma background value) without importing cooking fumes; (ii) cooking fumes pass through WSB/PR; and (iii) cooking fumes pass through ESB/PR. When cooking fumes are treated with WSB/PR, light emission intensity intensifies with increased plasma power, from 0.112 kJ/m³ to 0.146 kJ/m³. The same tendency occurs in the situation of cooking fumes treated with ESB/PR, which increases plasma power from 0.112 kJ/m³ to 0.138 kJ/m³. In addition, the number of active species is reduced when plasma power is increased. This indicates that, electron energy is reduced due to the H₂O decomposition function in the plasma reaction, which results in a decrease in the number of active species.

Keywords: Plasma; Cooking fumes; OES (optical emission spectra); Active species; Free radicals.

INTRODUCTION

Cooking fumes produced from kitchens or restaurants that are not treated by any pollution control devices will lead to pollution in residential areas and public concern. Previous studies indicate that cooking fumes contain many compounds with carcinogenicity and mutagenicity, such as PAHs, alkanes, ketone, acids, and amides. (Rogge *et al.*, 1991; Chiang *et al.*, 1999; Zhu *et al.*, 2003; He *et al.*, 2004; Zhao *et al.*, 2007; Li *et al.*, 2012) Long-term exposure to these substances may cause pathological changes of

respiratory systems, which may lead to cancer. Thus, the health concern of cooking fumes should draw serious attention (Chowdhury *et al.*, 2012; Pervez *et al.*, 2012; Kristensson *et al.*, 2013), and technological developments for cooking fume treatments should be discussed.

The development of plasma technology has witnessed a history of more than 10 years, and technologies have been widely applied in various fields, such as machinery, chemical industries, materials, and environmental protection. With the advancement of plasma technology, many plasma reactors (PR) have been developed for environmental research, such as radio frequency plasma, microwave plasma, and corona discharge methods, in order to control and treat pollutants (Shih *et al.*, 2003; Yan *et al.*, 2006; Wang *et al.*, 2007; Chang *et al.*, 2013; Lin *et al.*, 2013). Wang *et al.* (2003) studied decomposition of boron trifluoride in the RF plasma environment and showed the reaction in the BF₃/O₂/Ar

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plasma system generated B_2O_3 fine particles and led to the deposition of a white substance on the surface of the reactor. Wang *et al.* (2005) studied direct conversion of methane into methanol and formaldehyde in an RF plasma environment and found that in an Ar stream, the CH_3OH conversion ratio in the CH_4/O_2 plasma system was higher than that in CH_4/CO , CO/H_2 and $CH_4/H_2/O_2$ plasma systems. The conversion of CH_4 reached 19.1% at $CH_4/O_2 = 40/60$; the yield of CH_3OH was 1.12% and 16.0% CO , the major product, was produced. Liao *et al.* (2005) studied reaction mechanism of ethylene oxide at various oxygen/ethylene oxide ratios in an RF cold plasma environment and showed the main reactions for EO decomposition changed with a varying O_2/EO ratio in the plasma system. Tsai *et al.* (2007) studied conversion of carbonyl sulfide using a low-temperature discharge approach and results showed that at an inlet O_2/COS molar ratio of 3, the removal efficiency of COS reached 98.4% at 20 W and 4000 N/m^2 , with the major product being SO_2 with small amounts of sulfur deposition. The removal efficiency of COS was lower in the H_2 -containing condition than in the O_2 -containing one. Subramanian *et al.* (2009) studied thermal plasma synthesis of iron oxide aerosols and their characteristics and showed that quantification of Fe^{2+} and Fe^{3+} present in the aerosol deposits showed that the generation of Fe^{2+} has been enhanced by 2% when the sheath gas is changed from air to nitrogen. Previous studies have pointed out that, the abovementioned methods can deal with pollutants in the gaseous phase, as plasma can decompose hazardous substances into non-toxic substances or gas molecules due to high-temperature properties.

Optical emission spectroscopy (OES) provides a non-invasive probe to investigate atoms, ions and molecules within a plasma. This technique is especially effective for plasma diagnosis because of no disturbance. On the other hand, it is known that the emission intensity of the sputtered particle is strongly affected by oxygen atoms adsorbed on the surface (Motohashi *et al.*, 2011). In general, Optical Emission Spectroscopy (OES) can assist the analysis of environmental trace pollutants, such as heavy metals, trace materials and air toxics. OES allows low detection limits and has found wide applications in the determination of trace levels of arsenic combined with atomic absorption spectrometry (Näykki, *et al.*, 2001), atomic fluorescence spectrometry (AFS) (Leal *et al.*, 2004) or coupled with optical emission spectroscopy-inductively coupled plasma (ICP-OES) (Anthemidis *et al.*, 2006; Gil *et al.*, 2007). Moreover, correlation between the OES plasma composition and the diamond film properties was also studied by Vandeveld *et al.* (1999) during microwave PA-CVD with nitrogen addition. Optical emission spectroscopy (OES) is used to survey the plasma composition during deposition. The intensities of the CN , CH and C_2 emitting radicals and the Balmer atomic hydrogen emission lines are correlated to the Raman film quality and to the nitrogen content in the film measured by secondary ion mass spectrometry (SIMS) (Vandeveld *et al.*, 1999).

In analysis of plasma diagnosing, the optical emissions spectrum (OES) is often used in plasma systems to monitor

and diagnose non-intrusive chemical composition and free radical species. However, at present, only a few studies focus on treating cooking fumes with plasma technology, while most study the compounds of cooking fumes. Especially, the study relevant to the analysis of plasma diagnosing in the treating process of cooking fume is lack of research.

As far as researchers are concerned, it still remains a challenge to make the processes effective and practical due to a lack of full understanding on the considerable complexity of fundamental plasma physics and plasma chemistry involved in the interaction between thermal plasma and polluted cooking fume. Therefore, this study attempted to treat cooking fumes by guiding the fumes into a self-designed and assembled wet scrubber (WSB or ESB solution)/plasma reactor (PR) system through a cooking fume generator, and then monitored the spectral lines of the OES during the reaction process using an OES at the rear end of PR. Finally, this study compared the databases of spectral lines from the experiment in order to identify the properties of OES using atmospheric pressure plasma to treat cooking fumes.

METHODS

Experiment

Cooking Fumes Generator

In this experiment, the pork was placed flat in a self-made tray (aluminum foil folded; 25 cm × 35 mm, thickness of 5mm), the pork was placed into an electric oven for heating (actual temperature is 180 to 190 degree Celsius), and the cooking fumes were guided to the rear end of the WSB and PR through a kitchen ventilator (HCG brand, model SE185, dimension 715 × 570 × 190 mm, and double fan $\Phi 240$ mm).

Washing Equipment for Cooking Fumes

This system consisted of a high-pressure power sprayer and WSB (W × H; 30 × 100 cm) of plastic material (high-density polyethylene). The water volume of the spray was 14 L/min, the pressure setting for spray was 10 kg/cm^2 ; 25L enzyme scrubbing solution, which was later recycled, was used in each experiment. The enzyme solution ingredient was show at 2.2 experimental materials.

Plasma-generating Source

The plasma devices (model: IGBT, air plasma of inverter G-CUT 51P, input current: 10 KVA, input voltage 220 V/60 Hz, output current 10–50 A, weight: 17.5 kg, and dimension with 470 × 204 × 350 mm) used in this study were produced by the Taiwan Plasma Company. The air compressor (specification 1HP) was synchronically started with the plasma in order to avoid damage to machine caused by overheating of the plasma electrode.

Optical Emission Spectrometer (OES)

The resolution of the OES (brand: Ocean Optics, model: HR 4000 CG) was 0.7 nm, and the measurement range of wavelength was from 200–1100 nm. The measurement method was to place a light-source detector into the plasma system (the position is 60 cm from the plasma torch),

transmitting lights to OES for signal reading by applying optical fiber (specification 200 μm), connecting to a computer to display different spectrums, and identifying active species by comparing databases.

Experimental Materials

The source of the cooking fumes in the experiment was from lean and fat pork (proportion: 5:3). The pork was placed into a meat grinder for mincing and mixing. In each experiment, 180 g of mixed pork was placed into the electric oven for heating. The scrubbing solution used in the experiment was tap water and an enzyme scrubbing solution (diluting the enzyme stock solution with tap water for 100 times). The volume of the scrubbing solution was 25 liters. Enzyme stock solution was an aqueous solution compound, created by mixing certain proportions of molasses, soybean meal, rice bran, rice wine, vinegar, and trace minerals (iron, aluminum, magnesium, silicon, etc.) with water. Lastly, the solution was separated and purified under the active development of flora, such as emulsified acid bacteria, acidophil, and photosynthetic bacteria (Chen *et al.*, 2003; Lin *et al.*, 2006; Chen *et al.*, 2008; Lin *et al.*, 2008).

Experimental Method

Output Power of Plasma

Based on the range of operational steady conditions, when the output power of the plasma reactor was controlled from 0.112 kJ/m^3 to 0.156 kJ/m^3 , the maximum entry temperatures were roughly from 1589 K to 2804 K, respectively. In the reactor, the temperature along the exhaust tube was homogeneous, while the plasma torch profile was

asymmetrical because of the range hood gas flow. In all cases, the volume of the atmospheric plasma reaction zone was 0.01049 m^3 , and the average retention time was 0.10638 s. The energy of the plasma varied with the changes of input power, thus, this study chose five output powers (0.112 kJ/m^3 , 0.129 kJ/m^3 , 0.138 kJ/m^3 , 0.146 kJ/m^3 , and 0.156 kJ/m^3) as the conditions of experimental operations.

Detection Theory of Emission Spectra

The measurement theory of OES is to detect photons with different wavelengths radiated by gas species in a plasma environment. The photons are the result of inelastic collisions of high-energy electrons with ions, neutral atoms, or molecules. When struck by high-energy electrons, gas particles stimulate the particles from a low-energy state to an excited state. Moreover, those electrons return to their ground state and release energy in the form of light, after undergoing de-excitation or relaxation. Quantitative analysis can be conducted through the intensity of different wavelengths, thus, qualitative analysis on elements and species contained in plasma is conducted when applying OES for analysis. Generally, the wavelength coverage of spectral analysis for emission spectrometer is between 200 nm and 900 nm, which covers ultraviolet light and visible spectral lines. The spectrum requires a wavelength of less than 190 nm in order to avoid oxygen absorption. Regarding the spectra with wavelengths over 900 nm, their electrons emit weaker and less common light signals upon being excited and transferred.

The method of measuring plasma with OES is to gather the emission signals of atoms, ions, and molecules, which are excited in the plasma to the head of the optical fiber by

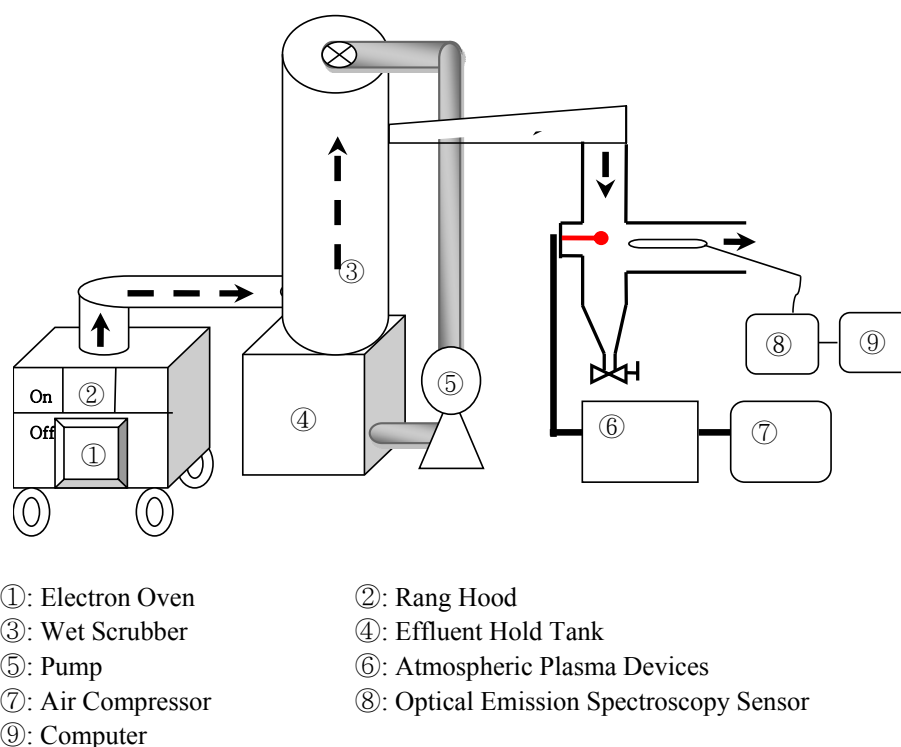


Fig. 1. Schematic of the experimental system.

applying a collimator. The light is guided into the signals, and is connected to a computer to display the spectra. The emission components in plasma are mainly excited atoms and molecules (diatomic molecules, e.g., N_2), while the intensity of light given off by excited ions, polyatomic molecules (e.g., CH_4), and free radicals (e.g., CH_3) is too weak to be easily observed (Liao, 2004).

RESULTS AND DISCUSSION

In the process of damage reduction for plasma, there is a

spectrograph through an optical fiber, which reads the relative relation between active species and products. In order to understand the effects of operational parameters on active species, this study applied optical emission spectroscopy to measure the intensity of optical emission spectra for active species of cooking fumes in the treatment process of plasma, and compared the differences of OES before and after the plasma reaction.

Spectral Analysis of Atmospheric Pressure Plasma

Fig. 2 is the plasma emissions spectra graph (plasma

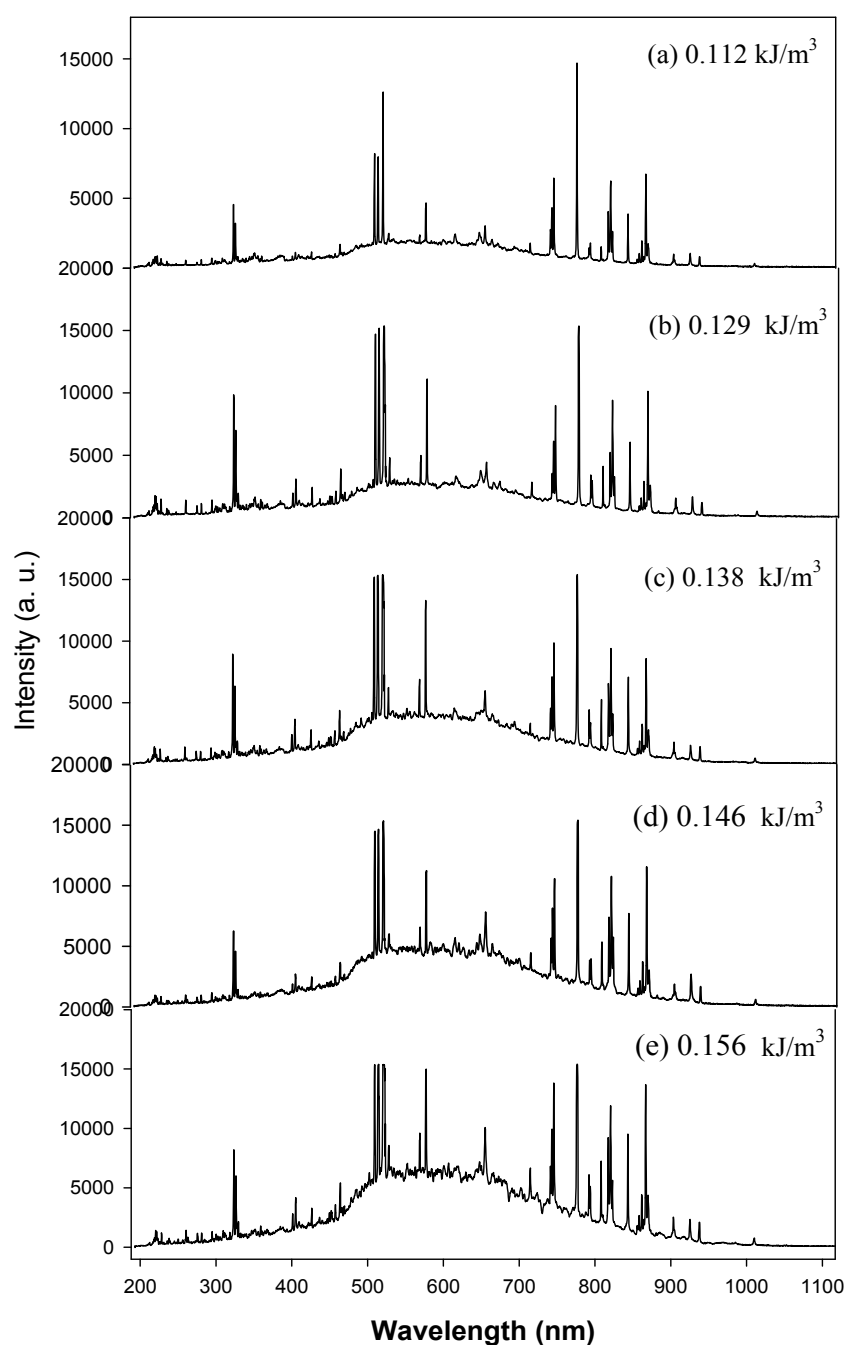


Fig. 2. Optical emission spectroscopy intensity in the atmospheric plasma test (background). (a) 0.112 kJ/m^3 ; (b) 0.129 kJ/m^3 ; (c) 0.138 kJ/m^3 ; (d) 0.146 kJ/m^3 ; (e) 0.156 kJ/m^3 .

background value) measured without guiding any cooking fumes into the system of PR under the output powers of 0.112 kJ/m³, 0.129 kJ/m³, 0.138 kJ/m³, 0.146 kJ/m³, and 0.156 kJ/m³. The results show that the active species of C (492.6 nm, 505.2 nm, 538 nm), C₂ (516.4 nm, 563.3 nm), CH (314.4 nm), CN (359 nm, 388 nm), Hγ (433.9 nm), N₂ (357 nm, 580.4 nm), N₂⁺ (427.8 nm), NO (237 nm), C⁺ (386.9 nm), NH (337 nm), and O₂⁺ (526 nm, 545 nm) exist in a wavelength ranging from 300 to 599 nm. In the range of 600 to 900 nm, there are active species: N₂ (646.9 nm, 891.2 nm), H₂ (601.8 nm), O (846.3 nm), and N (746.8 nm). Fig. 2 shows that intensities of spectral lines in the graph are significantly increased as the power is increased.

The intensity of active species is shown as in Table 2. Among five output powers, the highest measured intensity of active species are N₂ (646.9 nm) B³Π_g → A³Σ_u⁺ (first positive), and the remaining active species are O₂⁺ (545 nm) B⁴Σ_g⁻ → A²Π_u, C (538 nm), N₂ (580.4 nm) B³Π_g → A³Σ_u⁺ (first positive), and H₂ (601.8 nm) D³Π_u → A³Π_g⁺ H₂ (601.8 nm). The value of active species I_{PR 0.156 kJ/m³}/I_{PR 0.112 kJ/m³} Ratio is more than 1 (1.7–3.9), which displays in the PR system. The input of higher power can provide energy with more reaction gas. Increase the effective collisions of reactants and electrons in order to promote the quantity of active species in the system.

Different Handling Methods Characteristics of Spectral Intensity for Active Species

The light intensity of active species, as measured by the optical emissions spectrograph, cannot display the actual intensity of active species; however, it can indicate the relation of relative concentrations of active species. Figs. 3

and 4 show the WSB/PR for cooking fume, and OES graph of ESB/PR for cooking fumes, respectively. WSB/PR and ESB/PR can detect active species: C, C₂, CH, N, Hγ, N₂, N₂⁺, NO, C⁺, NH, O₂⁺, H₂, and O under the operation of five plasma output powers. Tables 3 and 4 show the intensity of active species for WSB/PR and ESB/PR.

When cooking fumes are guided into WSB/PR, the highest intensity of active species is N₂ (646.9 nm) B³Π_g → A³Σ_u⁺ (first positive) among the five output powers. The remaining active species are H₂ (601.8 nm) D³Π_u → A³Π_g⁺, N₂ (580.4 nm) B³Π_g → A³Σ_u⁺ (first positive), and C (538 nm). Conduct intensity comparison (I_{WSB/PR 0.129 kJ/m³}/I_{WSB/PR 0.112 kJ/m³}, I_{WSB/PR 0.138 kJ/m³}/I_{WSB/PR 0.112 kJ/m³}, I_{WSB/PR 0.146 kJ/m³}/I_{WSB/PR 0.112 kJ/m³}, I_{WSB/PR 0.156 kJ/m³}/I_{WSB/PR 0.112 kJ/m³}) of the active species (C, C₂, CH, N, Hγ, N₂, N₂⁺, NO, C⁺, NH, O₂⁺, H₂ and O) that have been detected in this study. The results show that the intensity of active species is 1.1–1.6 times, 0.9–1.8 times, 0.9–1.5 times, and 0.4–0.8 times, when the power of WSB/PR is 0.112 kJ/m³. In the reaction process of WSB/PR for cooking fumes, the intensity of active species is reduced as power is increased. The presumption is that, after being washed, cooking fumes reduce the electron energy in plasma reaction process as the H₂O decomposition function, which results in a quantity decrease of active species. When cooking fumes are guided into the ESB/PR, the highest intensity of active species is N₂ (646.9 nm) B₃Π_g → A₃Σ_u⁺ (first positive) among the five output powers. The remaining active species are N (746.8 nm) 2p³3s(4P) → 2p²3p(4S) and C (538 nm). Conduct intensity comparisons of active species (C, C₂, CH, N, Hγ, N₂, N₂⁺, NO, C⁺, NH, O₂⁺, H₂ and O) detected in this study. The results show that the four powers of ESB/PR relative to ESB/PR 0.112 kJ/m³ are 1.1–

Table 2. Intensity of active species for PR tests.

Active species	Wavelength (nm)	Transition	Plasma power (kJ/m ³)				
			0.112	0.129	0.138	0.146	0.156
			Intensity (unit: a.u.)				
C	493.2	--	1549.5	2129.7	3308.3	3796.8	4988.0
C	505.2	--	1655.3	2415.7	3357.3	4146.0	5667.3
C	538	--	1886.2	2926.0	4121.3	4651.0	6221.3
C ₂	516.4	A ³ Π _g → X ³ Π _u (swam system)	1864.8	2763.5	3961.2	4610.7	6273.7
C ₂	563.3	A ³ Π _g → X ³ Π _u (swam system)	1794.7	2698.8	4046.7	4429.8	6383.3
CH	314.4	C ² Σ ⁺ → X ² Π _u	398.8	565.8	604.0	594.2	684.2
CN	359	BΣ ⁺ → A ² Π	680.5	1457.8	1520.8	1223.8	1800.7
CN	388.3	BΣ ⁺ → A ² Π	866.2	1119.0	1245.5	1382.8	1699.7
H ₂	601.8	D ³ Π _u → A ³ Π _g ⁺	1892.0	2753.7	3684.8	4611.3	6655.0
Hγ	433.94	--	761.8	1121.0	1425.3	1712.0	2112.5
N	746.8	2p ³ 3s(4P) → 2p ² 3p(4S)	1590.3	2219.0	3123.7	3520.7	5478.5
N ₂	357.7	C ³ Π _u → B ³ Σ _g (second positive)	453.5	621.2	692.2	753.3	887.3
N ₂	580.4	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	1830.5	2725.0	4083.2	4723.2	6132.2
N ₂	646.9	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	2376.5	3561.7	4173.0	5627.0	6827.0
N ₂	891.2	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	258.8	348.0	568.7	638.0	1006.3
N ₂ ⁺	427.8	B ³ Σ _u ⁺ → X ² Π _g ⁺	604.3	841.8	1148.0	1406.0	1635.0
NO	237	A ² Σ ⁺ → X ² Π	187.7	232.2	254.2	248.5	293.5
NH	337	A ³ Π → X ³ Σ	588.7	890.7	906.2	753.2	1011.7
O	846.3	2s ² 3p ³ (4S ⁰)3p → 2s ² 3p ³ (4S ⁰)3s	383.8	564.2	985.7	1106.0	1462.2
O ₂ ⁺	526	B ⁴ Σ _g ⁻ → A ² Π _u	1887.2	2594.2	3781.2	4602.0	6038.5
O ₂ ⁺	545	B ⁴ Σ _g ⁻ → A ² Π _u	1953.5	2662.0	3902.8	4563.0	6181.3

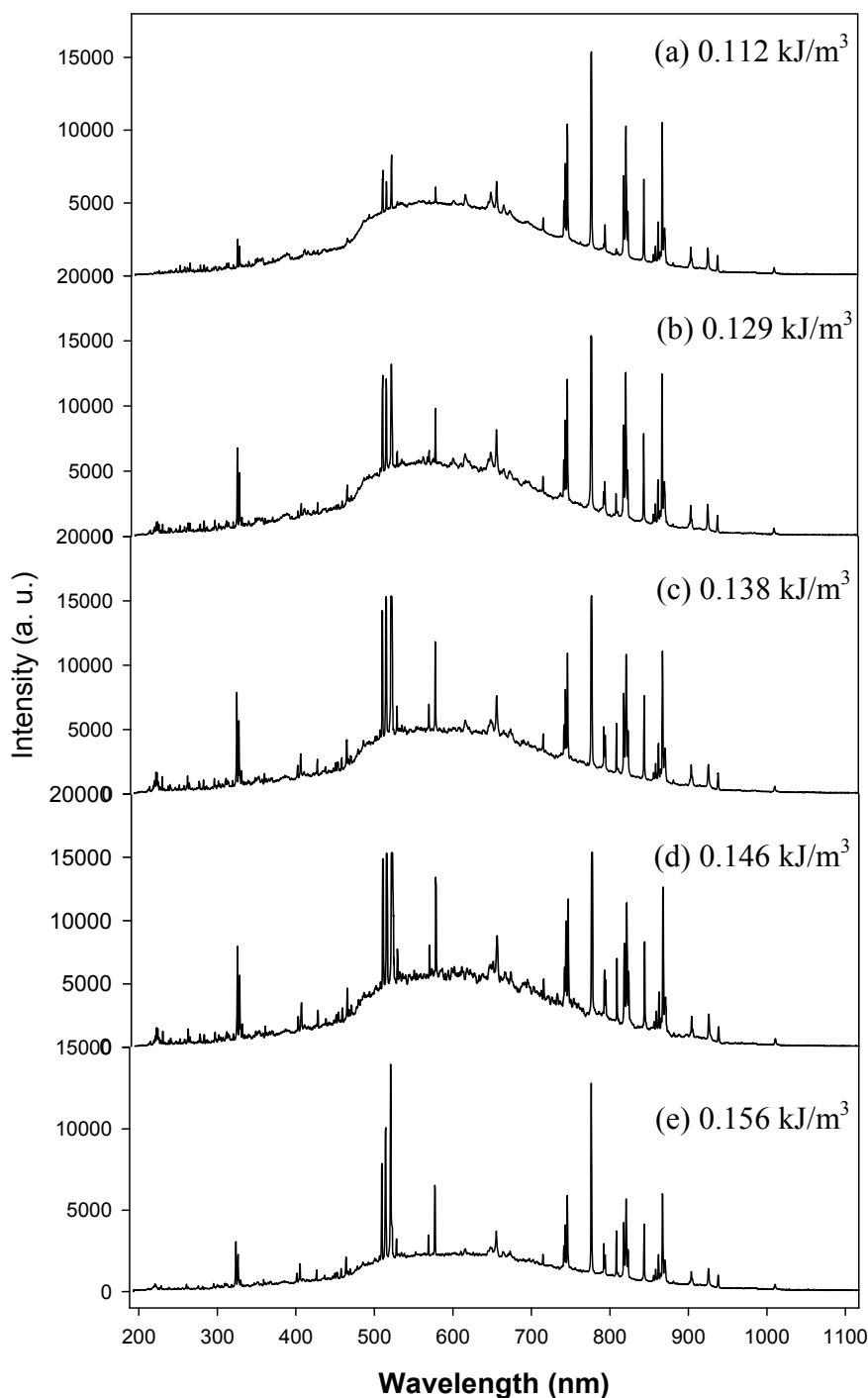


Fig. 3. Optical emission spectroscopy intensity in the WSB/PR test. (a) 0.112 kJ/m³; (b) 0.129 kJ/m³; (c) 0.138 kJ/m³; (d) 0.146 kJ/m³; (e) 0.156 kJ/m³.

1.5 times, 1.3–3.1 times, 1.3–2.9 times, and 1.3–3.2 times, respectively. The results also show that in the reaction process (specific value > 1) of the ESB/PR system, the intensity of active species is increases as the power is progressively increased. The presumption is that the organic substances (C, H, O, N, etc.) of the enzyme solution cause a quantity increase of active species in the plasma reaction process due to the high-temperature decomposition function.

CONCLUSIONS

The operating conditions set by this study are: (1) begin PR without guiding the cooking fumes; (2) WSB/PR for cooking fumes; and (3) ESB/PR for cooking fumes. Under five plasma powers (0.112 kJ/m³, 0.129 kJ/m³, 0.138 kJ/m³, 0.146 kJ/m³ and 0.156 kJ/m³), the active species (CH, CN, N₂, NH, C, Hγ, N₂⁺, C₂, O₂⁺, H₂, N and O) are detected in wavelengths of 300 to 900 nm. Among them, N₂ (646.9 nm)

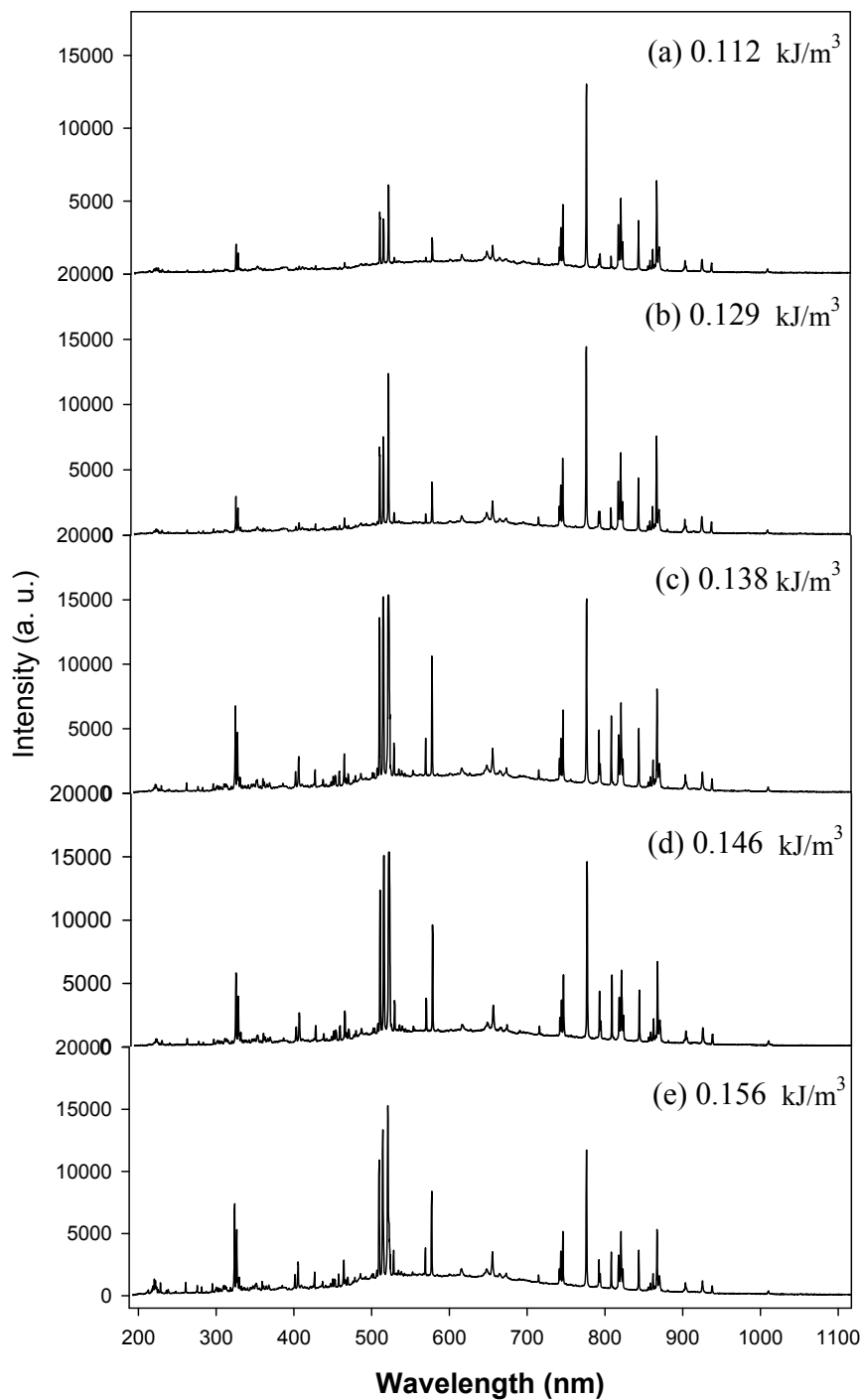


Fig. 4. Optical emission spectroscopy intensity in the ESB/PR test. (a) 0.112 kJ/m³; (b) 0.129 kJ/m³; (c) 0.138 kJ/m³; (d) 0.146 kJ/m³; (e) 0.156 kJ/m³.

$B^3\Pi_g \rightarrow A^3\Sigma_u^+$ (first positive) is the main dominant species. In the process of a WSB/PR system for cooking fumes, the active species tend to decline. The possible reason is that in the plasma reaction, the addition of steam (H_2O), allows extra electron energy release, which attributes to the decomposition of H_2O . Through this study, we observed that OES is useful on the analysis of plasma chemistry, especially for active species, in the plasma reaction under different operation situation. Thus, it is important to characterize the

active species in the plasma system with a rapid and portable way to identify the reaction situation.

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Table 3. Intensity of active species for WSB/PR tests.

Active species	Wavelength (nm)	Transition	Plasma power (kJ/m ³)				
			0.112	0.129	0.138	0.146	0.156
			Intensity (unit: a.u.)				
C	493.2	--	3971.0	4505.0	3965.67	3950.8	1687.8
C	505.2	--	4262.7	4662.2	4272.17	4681.3	1891.5
C	538	--	4861.0	5564.3	5209.00	5642.3	2333.0
C ₂	516.4	A ³ Π _g → X ³ Π _u (swam system)	4609.7	5366.0	4881.8	5043.3	2201.2
C ₂	563.3	A ³ Π _g → X ³ Π _u (swam system)	5022.3	5544.2	5006.0	5515.2	2304.3
CH	314.4	C ² Σ ⁺ → X ² Π _u	538.0	676.2	566.17	543.5	278.5
CN	359	BΣ ⁺ → A ² Π	886.5	1375.8	1589.2	1651.2	747.7
CN	388.3	BΣ ⁺ → A ² Π	1460.33	1692.2	1333.5	1301.5	594.3
H ₂	601.8	D ³ Π _u → A ³ Π _g ⁺	5050.0	5574.3	5104.5	5740.3	2358.0
Hγ	433.94	--	1797.83	2066.7	1782.8	1821.2	809.8
N	746.8	2p ³ 3s(⁴ P) → 2p ² 3p(⁴ S)	3707.8	4374.2	3950.5	5059.5	2239.7
N ₂	357.7	C ³ Π _u → B ³ S _g (second positive)	770.7	919.5	765.7	741.3	353.5
N ₂	580.4	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	4973.7	5635.0	4896.3	5565.0	2273.3
N ₂	646.9	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	5372.0	6024.2	5557.2	6317.2	2615.2
N ₂	891.2	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	623.8	666.2	713.5	804.7	465.7
N ₂ ⁺	427.8	B ³ Σ _u ⁺ → X ² Π _g ⁺	1451.5	1676.5	1428.5	1512	652.5
NO	237	A ² Σ ⁺ → X ² Π	220.2	311.2	298.33	265.5	156.2
NH	337	A ³ Π → X ³ Σ	617.5	880.7	903.2	866.3	381.3
O	846.3	2s ² 3p ³ (⁴ S ⁰)3p → 2s ² 3p ³ (⁴ S ⁰)3s	1045.2	1202.3	1175.8	1594.7	711.7
O ₂ ⁺	526	B ⁴ Σ _g ⁻ → A ² Π _u	4699.8	5320.8	4692.0	5130.7	2135.0
O ₂ ⁺	545	B ⁴ Σ _g ⁻ → A ² Π _u	4944.83	5513.2	4986.2	5457.7	2200.0

Table 4. Intensity of active species for ESB/PR tests.

Active species	Wavelength (nm)	Transition	Plasma power (kJ/m ³)				
			0.112	0.129	0.138	0.146	0.156
			Intensity (unit: a.u.)				
C	493.2	--	640.8	750.0	1075.0	981.7	1344.8
C	505.2	--	675.7	828.8	1209.3	1104.3	1445.5
C	538	--	808.3	982.5	1714.0	1614.0	1865.5
C ₂	516.4	A ³ Π _g → X ³ Π _u (swam system)	782.8	964.2	1619.3	1484.0	1821.3
C ₂	563.3	A ³ Π _g → X ³ Π _u (swam system)	853.3	926.5	1401.3	1267.3	1680.2
CH	314.4	C ² Σ ⁺ → X ² Π _u	228.5	244.5	311.8	287.3	391.5
CN	359	BΣ ⁺ → A ² Π	363.7	548.8	1129.7	1068.7	1152.8
CN	388.3	BΣ ⁺ → A ² Π	447.0	484.8	553.8	474.0	675.2
H ₂	601.8	D ³ Π _u → A ³ Π _g ⁺	926.7	1016.5	1485.2	1315.8	1640.3
Hγ	433.94	--	370.5	454.2	588.0	544.7	735.5
N	746.8	2p ³ 3s(⁴ P) → 2p ² 3p(⁴ S)	1173.5	1386.5	1762.2	1559.0	1525.0
N ₂	357.7	C ³ Π _u → B ³ S _g (second positive)	252.2	275.8	347.7	315.2	416.8
N ₂	580.4	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	884.8	915.5	1351.2	1237.3	1606.5
N ₂	646.9	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	1406.2	1546.0	2024.3	1766.2	1981.0
N ₂	891.2	B ³ Π _g → A ³ Σ _u ⁺ (first positive)	217.3	251.3	348.8	311.0	312.2
N ₂ ⁺	427.8	B ³ Σ _u ⁺ → X ² Π _g ⁺	284.0	343.2	456.5	407.2	566.0
NO	237	A ² Σ ⁺ → X ² Π	124.5	144.5	162.8	155.5	192.8
NH	337	A ³ Π → X ³ Σ	278.0	324.2	569.0	510.2	618.0
O	846.3	2s ² 3p ³ (⁴ S ⁰)3p → 2s ² 3p ³ (⁴ S ⁰)3s	325.7	384.2	534.7	464.8	472.2
O ₂ ⁺	526	B ⁴ Σ _g ⁻ → A ² Π _u	797.0	916.0	1389.0	1289.7	1656.7
O ₂ ⁺	545	B ⁴ Σ _g ⁻ → A ² Π _u	640.8	750.0	1075.0	981.7	1344.8

REFERENCES

- Alvarez, R., Quintero, M.C. and Rodero, A. (2004). Radical Distribution of Electron Density, Gas Temperature and Air Species in a Torch Kind Helium Plasma Produced at Atmospheric Pressure. *Spectrochim. Acta, Part B* 59: 709–721.
- Anthemidis, A.N. and Martavaltzoglou, E.K. (2006). Determination of Arsenic(III) by Flow Injection Solid Phase Extraction Coupled with on-line Hydride Generation

- Atomic Absorption Spectrometry Using a PTFE Turnings-Packed Micro-Column. *Anal. Chim. Acta* 573/574: 413–418.
- Chang, H.C. and Hsieh, L.T. (2013). Numerical Simulation of the Acenaphthylene Compound in an Atmospheric Plasma Reactor to Treat Cooking Fumes. *Aerosol Air Qual. Res.* 13: 122–136.
- Chen, C.C. and Lee, W.J. (2008). Using Oily Wastewater Emulsified Fuel in Boiler: Energy Saving and Reduction of Air Pollutant Emissions. *Environ. Sci. Technol.* 42: 270–275.
- Chen, H.L., Lee, H.M., Chen, S.H., Chang, M.B., Yu, S.J. and Li, S.N. (2009). Removal of Volatile Organic Compounds by Single-Stage and Two-Stage Plasma Catalysis Systems: A Review of the Performance Enhancement Mechanisms, Current Status, and Suitable Applications. *Environ. Sci. Technol.* 43: 2216–2227.
- Chen, S.J., Hsieh, L.T., Hwang, W.I., Xu, H.C. and Kao, J.H. (2003). Abatement of Odor Emissions from Landfills Using Natural Effective Microorganism Enzyme. *Aerosol Air Qual. Res.* 3: 87–99.
- Chiang, T.A., Wu, P.F., Wang, L.F., Lee, H., Lee, C.H. and Ko, Y.C. (1997). Mutagenicity and Polycyclic Aromatic Hydrocarbon Content of Fumes from Heated Cooking Oils Produced in Taiwan. *Mutat. Res.* 381: 157–161.
- Chowdhury, Z., Le, L.T., Masud, A.A., Chang, K.C., Alauddin, M., Hossain, M., Zakaria, A. and Hopke, P.K. (2012). Quantification of Indoor Air Pollution from Using Cookstoves and Estimation of Its Health Effects on Adult Women in Northwest Bangladesh. *Aerosol Air Qual. Res.* 12: 463–475.
- Cicala, G., Bruno, P., Losacco, A.M. and Mattei, G. (2004). Plasma Deposition of Hydrogenated Diamond-Like Carbon Films from CH₄-Ar Mixtures. *Surf. Coat. Technol.* 180–181: 222–226.
- Coburn, J.W. and Chen, M. (1980). Optical Emission Spectroscopy of Reactive Plasmas: A Method for Correlating Emission Intensities to Reactive Particle Density. *J. Appl. Phys.* 51: 3134–3136.
- Elliott, M.A., May, P.W., Petherbridge, J., Leeds, S.M., Ashfold, M.N.R. and Wang, W.N. (2000). Optical Emission Spectroscopic Studies of Microwave Enhanced Diamond CVD Using CH₄/CO₂ Plasmas. *Diamond Relat. Mater.* 9: 311–316.
- Gil, R.A., Ferrúa, N., Salonia, J.A., Olsina, R.A. and Martinez, L.D. (2007). On-line Arsenic Co-precipitation on Ethyl Vinyl Acetate Turning-Packed Mini-column Followed by Hydride Generation-ICP OES Determination. *J. Hazard. Mater.* 143: 431–436.
- Goujon, M., Belmonte, T. and Henrion, G. (2004). OES and FTIR Diagnostic of HMDSO/O₂ Gas Mixtures for SiOx Deposition Assisted by RF Plasma. *Surf. Coat. Technol.* 188–189: 756–761.
- Hassan, C., Jamal, B., Michel, R. and Patrick, A. (1999). Optical Emission Diagnostics of Permanent and Pulsed Microwave Discharges in H₂-CH₄-N₂ for Diamond Deposition. *Surf. Coat. Technol.* 116–119: 1233–1237.
- Hsueh, H.P., McGrath, R.T., Ji, B., Felker, B.S., Langan, J.G. and Karwacki, E.J. (2001). Ion Energy Distribution and Optical Emission Spectra in NF₃-based Process Chamber Plasma. *J. Vac. Sci. Technol., B* 19: 1346–1357.
- Huang, H., Tang, L. and Wu, C.Z. (2003). Characterization of Gaseous and Solid Product from Thermal Plasma Pyrolysis of Waste Rubber. *Environ. Sci. Technol.* 37: 4463–4467.
- Jeong, B.Y. and Kim, M.H. (2001). Effects of the Process Parameters on the Layer Formation Behavior of Plasma Nitrided Steel. *Surf. Coat. Technol.* 141: 182–186.
- Jeong, H.K., Kim, S.H., Han, C., Lee, H., Song, H.K. and Na, B.K. (2001). Conversion of Methane to Higher Hydrocarbons in Pulsed DC Barrier Discharge at Atmospheric Pressure. *Korean J. Chem. Eng.* 18: 196–201.
- Kim, S.S., Lee, H., Na, B.K. and Song, H.K. (2004). Plasma-Assisted Reduction of Supported Metal Catalyst Using Atmospheric Dielectric-Barrier Discharge. *Catal. Today* 89: 193–200.
- Kristensson, A., Rissler, J., Löndahl, J., Johansson, C. and Swietlicki, E. (2013). Size-Resolved Respiratory Tract Deposition of Sub-Micrometer Aerosol Particles in a Residential Area with Wintertime Wood Combustion. *Aerosol Air Qual. Res.* 13: 24–35.
- Leal, L.O., Semenova, N.V., Forteza, R. and Cerd'a, V. (2004). Preconcentration and Determination of Inorganic Arsenic Using a Multisyringe Flow Injection System and Hydride Generation-atomic Fluorescence Spectrometry. *Talanta* 64: 1335–1342.
- Lee, S., Liu, S.J. and Liang, R.J. (2008). Optical Emission Study of Radio-Frequency Excited Toluene Plasma. *J. Phys. Chem. A* 112: 13500–13506.
- Li, Z., Mu, L., Peng, L., Bai, H.L., Liu, X.F. and Du, B. (2012). Correlation between the Concentration of Aromatic Hydrocarbons and BaP from Coke Oven Fugitive Emissions in Shanxi, China. *Aerosol Air Qual. Res.* 12: 1373–1378.
- Liao, W.T., Wei, T.C., Hsieh, L.T., Tsai, C.H. and Shih, M.L. (2005). Reaction Mechanism of Ethylene Oxide at Various Oxygen/Ethylene Oxide Ratios in an RF Cold Plasma Environment. *Aerosol Air Qual. Res.* 5: 185–203.
- Lin, Y.C., Lee, W.J., Chao, H.R., Wang, S.L., Tsou, T.C., Chang-Chien G.P. and Tsai, P.J. (2008). Approach for Energy Saving and Pollution Reducing by Fueling Diesel Engines with Emulsified Biosolution/Biodiesel/Diesel Blends. *Environ. Sci. Technol.* 42: 3849–3855.
- Lin, Y.C., Lee, W.J., Chen, C.C. and Chen, C.B. (2006). Saving Energy and Reducing Emissions of Both Polycyclic Aromatic Hydrocarbons and Particulate Matter by Adding Bio-Solution to Emulsified Diesel. *Environ. Sci. Technol.* 40: 5553–5559.
- Lin, Y.C., Yang, P.M. and Chen, C.B. (2013). Reducing Emissions of Polycyclic Aromatic Hydrocarbons and Greenhouse Gases from Engines Using a Novel Plasma-Enhanced Combustion System. *Aerosol Air Qual. Res.* 13: 1107–1115.
- Makabe, T. and Petrovic, Z.L. (2002). Development of Optical Computerized Tomography in Capacitively Coupled Plasma and Inductively Coupled Plasma for Plasma Etching. *Appl. Surf. Sci.* 192: 88–114.
- Näykki, T., Perämäki, P., Kujala, J. and Mikkonen, A. (2001).

- Optimization of a Flow Injection Hydride Generation Atomic Absorption Spectrometric Method for the Determination of Arsenic, Antimony and Selenium in Iron Chloride/Sulfate-based Water Treatment Chemical. *Anal. Chim. Acta* 439: 229–238.
- NIST, <http://physics.nist.gov/PhysRefData/Handbook/index.html>, Available on 2014/1/2.
- Park, Y.B. and Rhee, S.W. (2004). Low Temperature Silicon Dioxide Film Deposition by Remote Plasma Enhanced Chemical Vapor Deposition: Growth Mechanism. *Surf. Coat. Technol.* 179: 229–236.
- Pervez, S., Dubey, N., Watson, J.G., Chow, J. and Pervez, Y. (2012). Impact of Different Household Fuel Use on Source Apportionment Results of House-Indoor RPM in Central India. *Aerosol Air Qual. Res.* 12: 49–60.
- Rie, K.T., Menthe, E. and Whole, J. (1998). Optimization and Control of a Plasma Carburizing Process by Means of Optical Emission Spectroscopy. *Surf. Coat. Technol.* 98: 1192–1198.
- Rogge, W.F., Hildemann, L.M., Marurek, M.A. and Cass, G.I. (1991). Sources of Fine Organic Aerosol. 1. Charbroilers and Meat Cooking Operations. *Environ. Sci. Technol.* 25: 1112–1125.
- Shih, M., Lee, W.J. and Chen, C.Y. (2003). Decomposition of SF₆ and H₂S Mixture in Radio Frequency Plasma Environment. *Ind. Eng. Chem. Res.* 42: 2906–2912.
- Subramanian, V., Baskaran, R. and Krishnan, H. (2009). Thermal Plasma Synthesis of Iron Oxide Aerosols and Their Characteristics. *Aerosol Air Qual. Res.* 9: 172–186.
- Timmermans, E.A.H., Jonkers, J., Rodero, A., Quintero, M.C., Sola, A., Gamero, A., Schram, D.C. and Mullen, van der JAM. (1999). The Behavior of Molecules in Microwave-Induced Plasma Studies by Optical Emission Spectroscopy. 2: Plasma at Reduced Pressure. *Spectrochim. Acta, Part B* 54: 1085–1098.
- Tsai, C.H., Tsai, P.S., Jou, C.J.G. and Liao, W.T. (2007). Conversion of Carbonyl Sulfide Using a Low-Temperature Discharge Approach. *Aerosol Air Qual. Res.* 7: 251–259.
- Wang, X., Wang, A., Wang, X. and Zhang, T. (2007). Microwave Plasma Enhanced Reduction of SO₂ to Sulfur with Carbon. *Energy Fuels* 21: 867–869.
- Wang, Y.F., Lee, W.J., Chen, C.Y. and Hsieh, L.T. (1999). Decomposition of Dichlorodifluoromethane by Adding Hydrogen in a Cold Plasma System. *Environ. Sci. Technol.* 33: 2234–2240.
- Wang, Y.F., Tsai, C.H., Hsieh, L.T., Shih, M.L. and Chang, W.C. (2003). Decomposition of Boron Trifluoride in the RF Plasma Environment. *Aerosol Air Qual. Res.* 3: 53–59.
- Wang, Y.F., Tsai, C.H., Shih, M.L., Hsieh, L.T. and Chang, W.C. (2005). Direct Conversion of Methane into Methanol and Formaldehyde in an RF Plasma Environment I: A Preliminary Study. *Aerosol Air Qual. Res.* 5: 204–210.
- Yan, N.Q., Qu, Z., Jia, J.P., Wang, X.P. and Wu, D. (2006). Removal Characteristics of Gaseous Sulfur-Containing Compounds by Pulsed Corona Plasma. *Ind. Eng. Chem. Res.* 45: 6420–6427.
- Zh, L.H. and Wang, J. (2003). Sources and Patterns of Polycyclic Aromatic Hydrocarbons Pollution in Kitchen Air, China. *Chemosphere* 50: 611–618.
- Zhao, Y., Hu, M., Slanina, S. and Zhang, A. (2007). Chemical Compositions of Fine Particulate Organic Matter Emitted from Chinese Cooking. *Environ. Sci. Technol.* 41: 99–105.

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