Towards Ideal NOx and CO2 Emission Control Technology for Bio-Oils Combustion Energy System Using a Plasma-Chemical Hybrid Process

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Abstract. A pilot-scale low-emission boiler system consisting of a bio-fuel boiler and plasma-chemical hybrid NOx removal system is investigated. This system can achieve carbon neutrality because the bio-fuel boiler uses waste vegetable oil as one of the fuels. The plasma-chemical hybrid NOx removal system has two processes: NO oxidation by ozone produced from plasma ozonizers and NO2 removal using a Na2SO3 chemical scrubber. Test demonstrations of the system are carried out for mixed oils (mixture of A-heavy oil and waste vegetable oil). Stable combustion is achieved for the mixed oil (20 – 50% waste vegetable oil). Properties of flue gas—e.g., O2, CO2 and NOx—when firing mixed oils are nearly the same as those when firing heavy oil for an average flue gas flow rate of 1000 Nm3/h. NOx concentrations at the boiler outlet are 90 – 95 ppm. Furthermore, during a 300-min continuous operation when firing 20% mixed oil, NOx removal efficiency of more than 90% (less than 10 ppm NOx emission) is confirmed. In addition, the CO2 reduction when heavy oil is replaced with waste vegetable oil is estimated. The system comparison is described between the plasma-chemical hybrid NOx removal and the conventional technology.

1. Introduction
A series of studies have been conducted on laboratory-scale nonthermal plasma-chemical hybrid processes for the removal of NOx from gases emitted from various stationary sources such as boilers, diesel power generators and refuse incinerators. These processes can now successfully remove almost all traces of NOx with negligible amounts of byproducts [1]–[7]. However, because the flue gases must be treated directly, treatment of large volumes requires both a large plasma reactor and a large amount of power. An alternative process has been developed that involves the injection of ozone (O3) or radicals generated from oxygen (O2), ammonia (NH3), nitrogen (N2) and methane (CH4) by using plasma (indirect plasma method). This process has been studied in laboratory-scale and pilot-scale experiments [8]–[18], where it has been found to be extremely effective for NOx removal, because only the necessary amounts of gas—e.g., ambient air, O2, NH3, CH4 and N2—are treated externally at ambient temperature and pressure. Therefore, the indirect plasma method is more economical than the direct plasma method in terms of construction and operating costs for plasma generation; it also

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requires less installation space. NOx removal using the ozone injection method for diesel engine exhaust gas and the simultaneous removal of NOx and SO2 from the flue gas of a thermal power station have been reported [14]–[18].

On the basis of the laboratory-scale experimental studies, tests on the removal of both NOx and SOx from the gas emitted from a boiler were carried out using our first pilot-scale apparatus employing the indirect plasma-chemical hybrid process [19]. This apparatus consisted of a pulsed corona plasma reactor that produced mainly O3 from ambient air and a chemical scrubber (diameter: 0.9 m) that required a manual supply of chemical solutions. The NOx removal efficiency during the combustion of city natural gas exceeded 90%. However, during the combustion of heavy oil, the efficiency was only about 60% because sufficient O3 could not be generated with the available pulse power supply; in addition, the supply of chemical solutions was incomplete. The SOx removal efficiency was 85 – 90%. The waste water from the scrubber could be drained because it met the waste water regulation.

Our second pilot-scale apparatus [20]–[22] consisted of an ozonizer that was more compact and economical than the original pulsed corona reactor and a chemical scrubber that had approximately one-third the volume of the original. The scrubber was made smaller on the basis of the test results of the NOx removal process and included an automatic injection control for the chemical solutions. Continuous operation for 3 – 5 h was successful, and the NOx removal performance was confirmed during a preliminary test [20]. The performance characteristics were then investigated at flue gas flow rates of 410 – 1480 Nm3/h (N: Standard state) [21]. The amount of NOx removed was clearly dependent on the oxidation reduction potential (ORP) of the scrubbing solution, and it increased with a decrease in the ORP. To remove the required amount of NOx from the flue gas, the ORP should be maintained below 0 mV or as low as possible. However, because the ORP fluctuates over time, to maintain a stable NOx removal performance, the injection rate of fresh Na2SO3 solution should be sufficient to keep the rate of change in ORP at less than zero (0 mV/min). Furthermore, the influence of the packing material height in the scrubber on NOx removal performance characteristics was investigated [22]. The correlation between NOx removal efficiency and gas retention time was obtained; this provided an important index for scrubber design.

Our third generation demonstration plant was constructed from scratch. It consisted of a boiler that can use multi-fuels—not only compressed natural gas or heavy oil but also waste vegetable oil (WVO), etc.—and an improved chemical scrubber. WVO, which is mainly collected from snack food factories and fast food restaurants, differs from heavy oil in properties such as dynamic viscosity, flash point and fuel components. The scrubber size is optimized in terms of the flue gas condition, and an automatic injection control for both ozone and the chemical solution is included.

The objective of this study is to investigate the combustion characteristics of the third demonstration multi-fuel boiler system, confirm the performance characteristics of NOx removal when using plasma-chemical hybrid process and obtain practical operation details for the purpose of industrial application. In the first stage of the study, operation tests of the system are carried out for heavy oil, mixed oil (heavy oil and WVO) and city natural gas fuel.

2. Experimental apparatus and methods

Figure 1 shows an overview of the third demonstration plant. Figure 2 shows a schematic diagram of the plant. The boiler (Takao Iron Co., Ltd.) had a new type of a rotary burner for gas or oil fuels and is operated by using city natural gas (13 A type, Osaka Gas Co., LTD., Japan) at 157 Nm3/h, heavy oil (A type) at 147 kg/h and WVO as a fuel; this is the rated value of the boiler and is equivalent to a thermal output value of 1.57 MW. The boiler has a steam generation rate of 2.5 ton/h. An economizer (exhaust gas heat exchanger) is used to recover the heat energy from the flue gas and sufficiently reduce the temperature of the flue gas to less than 150°C at the scrubber inlet to keep the plasma-chemical reaction effective.
Figure 1. Frontal view and details of the third generation pilot-scale low-emission boiler system

Figure 2. Schematic diagram of the low-emission boiler system.

One or two sets of commercial ozonizers (Ebara Jitsugyo Co., Ltd., EW-90Z) with a pressure swing adsorption (PSA) oxygen generator (power = 1.6 kW) are employed for ozone generation as described in Table 1; when the O₃ gas flow rate is 0.9 Nm³/h and the discharge power is 1.5 kW, 90 g/h of ozone is generated, and its concentration is approximately 4.7%. The energy efficiency for ozone generation is 60 g/kW*h.

The ozone is injected into a flue gas duct for NO oxidation (NO + O₃ → NO₂ + O₂). The flue gas is then introduced into the scrubber with a height of 3.7 m to reduce NO₂ (2NO₂ + 4Na₂SO₃ → N₂ + 4Na₂SO₄). The diameters are 0.9 m at the sump part of the scrubber and 0.7 m at the packing material layer part. The scrubbing solution is pumped from the sump to the top of the scrubber and sprayed through a nozzle over the packing material. Two types of packing materials (Packing A and Packing B) are used. The total height is set to 1.2 m, which includes Packing A (0.3 m) and Packing B (0.9 m). Packing A is a No. 1-type Raschig Super-Ring (RSR) made of SUS304 (specific surface: 163 m²/m³; void fraction: 98%) piled beneath Packing B in the scrubber. Packing B is an S-II-type Tellerette
packing made of polypropylene (specific surface: 150 m²/m³; void fraction: 92%). After the NOx in the flue gas is removed in the scrubber, the cleaned flue gas is discharged in the air through the smokestack. On the other hand, the scrubbing solution passes through the packing layer into the sump is circulated by a multistage centrifugal pump operating at 0.5 kW. A small amount of scrubbing solution (50 – 100 L/h) is continuously drained from the scrubber to keep the activity of the solution, i.e., remove the reaction product from the scrubber solution. The liquid flow rate is set to 3.0 m³/h by controlling the valve at the outlet of the circulating pump. Meters installed on a tributary line connected to the sump monitored the ORP and pH of the scrubbing solution. To effectively remove NOx, maintaining a pH of more than 7 and an ORP of less than 0 mV for the scrubbing solution is essential. An aqueous solution of Na₂SO₃ and NaOH (concentrations: 200 g/L and 10 g/L) obtained from a chemical factory as a byproduct is continuously added into the sump. The flow rate of the fresh aqueous solution is carefully controlled according to the pH and ORP of the scrubbing solution. The initial Na₂SO₃ concentration of the scrubbing solution in the sump is set to more than 16 g/L. It is necessary to drain the waste aqueous solution from the scrubber. The waste fluid rate of aqueous solution depends on the flow rate of the flue gas. The waste liquid rate is approximately 100 L/h in this pilot plant. It is important to maintain the proper Na₂SO₃ concentration of the solution in order to continue stable plant operation.

| Table 1. Specifications of plasma ozonizer |
|------------------------------------------|
| **Type**                                | **EW-90Z**                                    |
| O₂ generation                            | PSA method (O₂ more than 90%)                 |
| O₃ generation                            | Air-cooled tubular                            |
| O₃ mass rate                             | Silent discharge                              |
| O₃ concentration                         | 0 – 90 g/h                                    |
| O₃ flow rate                             | 0 – 100 g/Nm³ = 4.7%                          |
| Power consumption                        | 0.9 Nm³ / h                                   |
| Power consumption                        | 1.6 kW (PSA), 1.5 kW (Discharge)              |
| Dimension                                | W740 × D925 × H1840 mm                        |

**Figure 3.** Structure of rotary-type boiler burner.
Figure 3 shows the rotary-type burner. This burner provides highly atomized characteristics for many kinds of oils such as light and heavy ones through centrifugal force generated by a high-speed rotating cup and primary combustion air injection. Secondary combustion air from the baffle plate helps enhance the flame-stabilizing and diffusion effects of the combustion air. Even fuel oils with unstable combustibility can be almost completely burned.

Experiments are performed after the temperature of the flue gas reached a steady state. The boiler is operated at 30 – 100% of the boiler rated load. The flow rate of the flue gas is not measured but determined by a practical formula based on the fuel consumption rate and O\textsubscript{2} concentration of the flue gas at the boiler outlet. The flue gas temperature is measured using thermocouples. The concentrations of the gaseous components (O\textsubscript{2}, CO\textsubscript{2}, CO, NO\textsubscript{x} and NO) are measured by using a gas analyzer (Horiba PG-240). The temperature of the flue gas and concentrations of its component are measured at the following three sampling points, as shown in Fig. 2: MP1 (boiler outlet), MP2 (scrubber inlet) and MP3 (scrubber outlet). The sampling points MP1 and MP2 are switched over after every measurement. The O\textsubscript{3} concentration generated by the ozonizer is measured by using an O\textsubscript{3} monitor (Ebara Jitsugyo Co., Ltd., EG-550) in the pipeline between the ozonizer and O\textsubscript{3} injection point of the flue gas duct.

Table 2. Oil Fuel properties.

| Fuel                     | Unit   | Heavy oil (A type) | Waste vegetable oil (WVO) |
|--------------------------|--------|--------------------|---------------------------|
| Low calorific value      | J/kg   | 44940              | 38880                     |
| Kinetic viscosity at 40°C | mm\textsuperscript{2}/s | 5~10               | 39                        |
| Flash point               | °C     | <60                | 296                       |
| Residual carbon           | %      | 0.06               | 0.15                      |
| Nitrogen                  | %      | 0.01               | <0.01                     |
| Sulfur                    | %      | 0.059              | <0.005                    |

Table 2 shows the fuel properties of both heavy oil and WVO. Because of relatively high viscosity, bio-fuel must be often preheated in the fuel tank when the temperature is low and/or filtered in the pipeline.

The experiments are carried out by firing heavy oil as the first step and then firing mixed oil as the second step. The mixture ratios of WVO to heavy oil are increased to 20%, 40% and 50% (vol.) in a stepwise fashion. The mixed oils are made up of 20%, 40% and 50% WVO corresponding to 80%, 60% and 50% (vol.) heavy oil, respectively (hereafter called 20%, 40% and 50% mixed oil). The experiment is carried out for 180 – 240 min on a single day.

3. Experimental results and discussion

Figure 4 shows the temperature of the flue gas at MP1, MP2 and MP3 when flow rates of the flue gas while firing the heavy oil are 930, 1560 and 2250 Nm\textsuperscript{3}/h, respectively. The temperature of the flue gas at MP1 reached 261°C when the flow rate of the flue gas is 2250 Nm\textsuperscript{3}/h. However, the temperature of the flue gas decreased to 126°C at MP2 when the economizer is in operation. The temperature of the flue gas at MP3 is below 56°C under all conditions.
Figure 4. Flue gas temperature vs. gas flow rate.

Figure 5. Gas components vs. gas flow rate when firing heavy oil. (Without plasma-chemical hybrid aftertreatment)
Figures 5(a) and (b) show the concentrations of O\textsubscript{2}, CO\textsubscript{2}, CO, NO and NO\textsubscript{x} at MP1 at flue gas flow rates of 930, 1560 and 2250 Nm\textsuperscript{3}/h, respectively. The concentration of O\textsubscript{2} is maintained in the range of 4.5%–5.4% in order to prevent the generation of both CO and particulate matter (PM). The concentration of CO is less than 1 ppm, and the concentration of CO\textsubscript{2} is 12.0% on average. On the other hand, the concentration of NO\textsubscript{x} decreased from 90 ppm to less than 80 ppm with increasing flow rate of the flue gas. The NO concentrations are 3 – 4 ppm less than those of NO\textsubscript{x}.

![Graph showing the relationship between NO removed and ozone concentration estimated in the gas duct.](image)

**Figure 6.** Relation between the amount of NO removed and the ozone concentration estimated in the gas duct.

Figure 6 shows the relationship between the amount of NO removed from the flue gas and the ozone concentration estimated in the flue gas duct where O\textsubscript{3} is injected. Flow rates of the flue gas are set to 930, 1560 and 2250 Nm\textsuperscript{3}/h, respectively, when firing heavy oil. The amount of NO removed is almost the same as the amount of the corresponding ozone concentration to oxidize NO to NO\textsubscript{2} (1:1 stoichiometric ratio) regardless of the flue gas flow rate. This proved that the distribution of ozone injected in the flue gas duct is good enough because that the flue gas duct is relatively small. However, in the case of scale-up of the system, a proper distribution of ozone is to be considered for larger gas duct.

After the heavy oil combustion test, mixed oil combustion tests are carried out to measure the flue gas components. Figures 7 (a)–(c) show the time-dependent flue gas components at MP1 when firing the mixed oils. The flow rates of the flue gas are 1090, 960 and 970 Nm\textsuperscript{3}/h when firing 20%, 40% and 50% mixed oils, respectively. For comparison between the mixed oils and heavy oil, the flue gas components when firing heavy oil are shown in these figures for the flow rate of 930 Nm\textsuperscript{3}/h of the flue gas. The average O\textsubscript{2} concentrations are 5.7%, 5.5% and 5.6% for 20%, 40% and 50% mixed oils, respectively. On the other hand, the average is 5.4% for heavy oil. The CO\textsubscript{2} concentrations are 11.5%, 11.8% and 11.7% for the mixed oils and 11.6% for heavy oil. Moreover, the CO concentrations are less than 1 ppm for all cases. Therefore, the mixed oils are fired under nearly the same conditions as heavy oil. Both the NO\textsubscript{x} and the NO concentrations plotted in Figs. 7(b) and (c) are the converted data at 4% O\textsubscript{2} in the flue gas; the measured concentrations of flue gas components at different O\textsubscript{2} concentrations are converted into the equivalent values at 4% O\textsubscript{2} to compare flue gas emissions. The NO\textsubscript{x} concentrations are almost the same at 97, 98 and 99 ppm on average for 20%, 40% and 50% mixed oils, respectively, and 98 ppm for heavy oil. The NO concentrations are also similar to NO\textsubscript{x}. Figures 7 (a)–(c) indicate that the concentrations of flue gas components remained almost unchanged and stable throughout the experiment for all cases, which is quite satisfactory for boiler combustion.
Figure 7. Gas components vs. gas flow rate when firing 20%, 40% and 50% mixed oils (without plasma-chemical hybrid aftertreatment)
Furthermore, boiler combustion and flue gas components need to be confirmed when firing other kinds of bio-fuels.

Figure 8. Result of the operation test of the system when the system is operated with heavy oil and plasma-chemical hybrid aftertreatment is carried out: (a) NOx and NO concentrations at MP1 (boiler exit) and MP3 (scrubber exit), (b) ORP and pH of the aqueous solution in the scrubber

Figure 8(a) shows the time-dependent NOx and NO concentrations at MP1 and MP3, respectively, during a 200-min operation period when firing heavy oil. For the first 20 min, the boiler is warmed up. Then after the boiler is operating at the corresponding fuel flow rate, measurement begins. The flow rate of the flue gas is set to 1360 Nm³/h. O₃ is injected at a rate of 153 g/h; this corresponded to an ozone gas flow rate of 1.8 Nm³/h. The scrubber solution flow rate is kept at 3.0 m³/h by maintaining the average injection rate of the Na₂SO₃ solution at 15.2 kg/h and that of the NaOH solution at 0.6 kg/h throughout the experiment. The concentrations of NO and NOₓ at MP1 are nearly constant until the end of the experiment. NO removal is on average from 85 ppm at MP1 to 10 ppm at MP3, and NOx removal is on average from 92 ppm at MP1 to 18 ppm at MP3; this is equivalent to a NOx removal efficiency of more than 80%. Figure 8(b) shows the time-dependent ORP and pH of the scrubbing solution when firing the heavy oil. The values of ORP and pH varied widely for 30 min after the plant started but then became stable owing to proper Na₂SO₃ injection control. The ORP and pH are maintained at approximately –50 mV and 8.2, respectively, which are satisfactory for scrubber operation. Stable performance of NOx removal is confirmed to have been achieved for a 200-min operation when firing heavy oil.

Figure 9(a) shows the time-dependent NOx and NO concentrations at MP1 and MP3, respectively, during a 300-min operation period when firing 20% mixed oil. The flow rate of the flue gas is set to 870 Nm³/h on average. O₃ is injected at a rate of 122 g/h. The scrubbing solution flow rate is kept at 3.0 m³/h by maintaining the average injection rate of the Na₂SO₃ solution at 11.7 kg/h and that of the NaOH solution at 0.5 kg/h throughout the experiment. Owing to a few changes in the O₂ concentration of 4.7 – 5.1%, NO and NOₓ at MP1 varied in the ranges of 80 – 93 and 90 – 105 ppm, respectively. However, NO is removed to less than 2 ppm at MP3. NO₃ is removed to less than 10 ppm at MP3; this is equivalent to a NO₃ removal efficiency of more than 90%. Figure 9(b) shows the time-dependent ORP and pH of the scrubbing solution when firing the 20% mixed oil. The values of ORP and pH varied widely for 30 min after the plant started but then became stable. The values of ORP and pH are maintained at approximately –30 mV and 8.1, respectively. A stable performance for NO₃ removal is confirmed to have been achieved for a 300-min operation when firing 20% mixed oil.
Figure 9. Result of the operation test of the system when the system is operated with 20% mixed WVO fuel and plasma-chemical hybrid aftertreatment is carried out: (a) NO\textsubscript{x} and NO concentrations at MP1 (boiler exit) and MP3 (scrubber exit), (b) ORP and pH of the aqueous solution in the scrubber.

Table 3 lists estimation results of the CO\textsubscript{2} reduction when firing bio-fuel. Waste vegetable oil is carbon neutral and is acknowledged to have less CO\textsubscript{2} emissions than other fuel types. When heavy oil (fuel rate: 147 kg/h) is burned at the rated value of the boiler, the concentration of CO\textsubscript{2} is calculated to be 11.6% in the flue gas, and the total amount of CO\textsubscript{2} emitted from the boiler is estimated to be 1,390 ton/year for 3,000 h of operation, as indicated by case 2 in the table. Therefore, if 50% mixed oil (50% heavy oil) is burned, CO\textsubscript{2} emission is reduced by 50% to 695 ton.

Table 3. Estimation of CO\textsubscript{2} reduction for bio-fuel firing.

| Items                                      | Unit   | Case 1 | Case 2 |
|--------------------------------------------|--------|--------|--------|
| Boiler load                                | %      | 40     | 100    |
| Fuel flow rate                             | L/h    | 68     | 171    |
| Total CO\textsubscript{2} emission (100% heavy oil) | t/y    | 555    | 1,390  |
| Total CO\textsubscript{2} reduction (20% WVO + 80% heavy oil) | t/y    | 444    | 1,110  |
| Total CO\textsubscript{2} reduction (50% WVO + 50% heavy oil) as carbon neutral | t/y    | 278    | 695    |

Remarks: Annual operation = 3,000 h

Figure 10 shows an example of measurement result on time-dependent NO\textsubscript{x} at MP1 and MP3 when the system is operated with city natural gas fuel. Flow rate of exhaust gas is $Q = 690$ Nm$^3$/h with CO\textsubscript{2} = 9.5%, O\textsubscript{2} = 4.5%. NO\textsubscript{x} concentrations are based on the equivalent value with O\textsubscript{2} = 5%. It is known from the figure that ultra-low NO\textsubscript{x} emission of less than 5 ppm is realized for 5 h.
4. Conclusions

The third pilot-scale low-emission boiler system for firing heavy oil and mixed oil (heavy oil and waste vegetable oil) is examined. Stable combustion is achieved for the mixed fuel (20 – 50% waste vegetable oil). Properties of flue gas—e.g., O₂, CO₂ and NOₓ—when firing mixed fuel are nearly the same as those in the case of firing heavy oil when the flue gas flow rate is 1,000 Nm³/h. NOₓ emission concentrations are 90 – 95 ppm. The effect of ozone injected into the flue gas is confirmed. The amount of NO removed is almost the same as the amount of the corresponding ozone concentration for oxidizing NO to NO₂.

Continuous operation tests of the system are successfully carried out for both heavy and mixed oil. When firing heavy oil, more than 80% of the NOₓ is demonstrated and confirmed to have been removed from the flue gas (less than 18 ppm at MP3) during a 200-min continuous operation for which the flue gas flow rate is 1360 Nm³/h and the ORP and pH are maintained at approximately 50 mV and 8.1, respectively. Furthermore, when firing 20% mixed oil, more than 90% of the NOₓ is removed from the flue gas (less than 10 ppm at MP3) during a 300-min continuous operation for which the flue gas flow rate is 870 Nm³/h, and the ORP and pH are maintained at approximately –30 mV and 8.0, respectively.

Mixed oil is successfully fired. The effect of replacing heavy oil with waste vegetable oil can reduce CO₂ emissions from the boiler. If 50% mixed oil (50% heavy oil) is burned, the amount of CO₂ discharged into the air is reduced by 50% to 695 ton for an 3000-h operation in 1 year.

The present De-NOₓ system is developed and effective for small size boiler application as compared to the conventional selective catalytic reduction (SCR) De-NOₓ system. For scale-up of the system there are necessary tunings to be confirmed; proper distribution of ozone injected in the flue gas duct and of scrubbing solution by spraying nozzle in the scrubber. For commercializing the system, the long-term operation tests are to be carried out to confirm the performance reliability of NOₓ removal and operational characteristics of the system.
Acknowledgments

The authors thank Mr. Y. Yoshioka, Mr. K. Takekoshi, Mr. Y. Nakagishi, Mr. Y. Fukumoto, and Mr. H. Mochizuki, all students of Osaka Prefecture University, for assistance with carrying out the experiments. This study is supported by the Regional Research and Development Resources Utilization Program conducted in the Japan Society Technology Agency (JST).

References

[1] Yamamoto T, Yang C L, Kravets Z, and Beltran M 2000 IEEE Trans. Ind. Appl. 36(3) 923–927
[2] Yang C L, Yamamoto T, Beltran M, and Kravets Z 1998 Env. Prog. 17(3) 183–189
[3] Yamamoto T, Okubo M, Hayakawa K, and Kitaura K 2001 IEEE Trans. Ind. Appl. 37(5) 1492–1498
[4] Kuroki T, Takahashi M, Okubo M, and Yamamoto T 2002 IEEE Trans. Ind. Appl. 38(5) 1204–1209
[5] Yoshida K, Yamamoto T, Kuroki T, and Okubo M 2009 Plasma Chem. Plasma Process. 29(5) 373–386
[6] Chang M B, Lee H M, Wu F and Lai C 2004 J. of Air & Waste Manage. Assoc. 54 941–949
[7] Okubo M, Kuroki T, Kitaura K, and Yamamoto T 2006 JSME, J. of Environment and Engineering 1(1) 29–38
[8] Yamamoto T, Kajimoto A, Okubo M, Kuroki T, and Yoshida K 2008 IEEE Trans. Ind. Appl. 44(5) 1431–1435
[9] Zhou Q, Yao S C, Russell A, and Boyle J 1992 J. of Air & Waste Manage. Assoc. 42(9) 1193–1197
[10] Nishida M, Yukimura K, Kambara S, and Maruyama T 2001 Jpn. J. Appl. Phys. 40 1114–1117
[11] Nishida M, Yukimura K, Kambara S, and Maruyama T 2001 J. Appl. Phys. 90(6) 2672–2677
[12] Dinelli G, Civitano L, and Rea M 1990 IEEE Trans. Ind. Appl. 26(3) 535–541
[13] Chang J S, Urashima K, Arquillq M, and Ito T 1998 Combust. Sci. and Tech. 133 31–47
[14] Sano K and Yoshioka Y 2003 IEEE Trans. FM 123(10) 1030–1035
[15] Yoshioka Y 2007 International J. Plasma Environmental Science and Technology 1(2) 110-122
[16] Simachev V Y, Novoselov S S, Svetlichnyi V A, Gavrilov A F, Gorokhov M V, Semenov V I, Ryzhikov V A, and Demchuk V V 1988 Thermal Engineering 35(3) 67–70
[17] Novoselov S S, Gavrilov A F, Simachev V Y, and Svetlichnyi V A 1986 Thermal Engineering 33 496–499
[18] Slater S M and Rizzone M S 1980 Fuel 59 897–899
[19] Yamamoto T, Fujishima H, Okubo M, and Kuroki T 2010 IEEE Trans. Ind. Appl. 46(1) 29–37
[20] Kuroki T, Fujishima H, Otsuka K, Ito T, Okubo M, Yamamoto T, and Yoshida K 2008 Thin Solid Films 516 6704–6709
[21] Fujishima H, Kuroki T, Ito T, Otsuka K, Okubo M, Yamamoto T, and Yoshida K 2010 IEEE Trans. Ind. Appl. 46(5) 1707–1714
[22] Fujishima H, Kuroki T, Tatsumi A, Tanaka A, Otsuka K, Yamamoto T, and Okubo M 2010 IEEE Trans. Ind. Appl. 46(5) 1722–1729