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論　　文

High Efficiency Ozone Generation Using a Pyramidally Embossed Rod-to-Cylinder Electrode and a Pulse Conora Discharge

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The conversion efficiency and matching condition of an ozone generator have been improved significantly by modifying the discharge electrode of an ozone generator to a pyramidally embossed rod and by using a pulse corona discharge. The generated ozone concentration was very dependent upon the value of pulse forming capacitance, feeder cable and ozone generator capacitance, and the tip-to-tip distance of discharge electrode. Maximum conversion efficiency was obtained with a pulse forming capacitance of about 500 pF, a matching capacitance of 75 pF for the feeder cable and the ozone generator, and a corona tip-to-tip distance of 4 mm. When operated under optimum conditions with cooled air feed an ozone yield ranging from 77 to 80 g/kWh for the 3 kinds of ozone generators tested was obtained.

1. Introduction

Ozone is one of the most powerful chemical oxidizers and has many applications in industry. But, however, its use in industry as an oxidizing agent has been limited by the relatively low conversion efficiency of the ozone generator. For example, typical commercial ozone generators utilize about 5% of the input power in ozone production.[1)]

It has been shown that the conversion efficiency and output ozone concentration of an ozone generator can be greatly increased by using a fast rising square wave AC voltage.[2-4)] And it has also been recognized that the production of ozone can be significantly enhanced by producing active and stable streamer coronas by applying a fast rising narrow pulse voltage on a corona discharge electrode.[5,6)]

This paper describes a new type ozone generator design, and, reports the results of an experimental investigation of its characteristics. This new development is based upon modifying the discharge electrode of a helical strip-line rod-to-cylinder type ozone generator to a pyramidally embossed rod electrode, which, however, is thought to have little inductance component of a corona electrode. Since a helical strip-line type ozone generator, proposed by author,[6)] had been found to have a difficulty in impedance matching with a pulse power generator due to its higher inductance induced by the long and thin helical strip-line, which had degraded the ozone production greatly. Parameters affecting ozone generation, such as value of peak pulse voltage and pulse forming capacitance of the pulse power generator, feeder cable and ozone generator capacitance, interelectrode spacing and pyramid tip-to-tip distance of discharge electrode, feed air flow rate and temperature, have been investigated to obtain optimum conditions of effective ozone generation in this paper.

2. Experimental Apparatus and Procedures

The test circuit diagram of an ozone generator with a fast rising high voltage pulse power generator used in the present investigations is illustrated in figure 1. The experiments were carried out at a fixed pulse repetition frequency, $f_p = 60$ pps, by rotating self triggered spark gaps with nickel plated stainless steel spark balls of 22 mm diameter. The polarity of the pulse voltage was also fixed only to a positive one which had been known to produce ozone effectively.[6)] Two kinds of high voltage coaxial cable, impedance of 75

Keywords: ozone generation, corona discharge, rod-to-cylinder electrode, pulse

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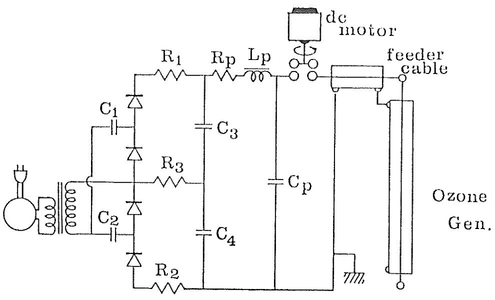
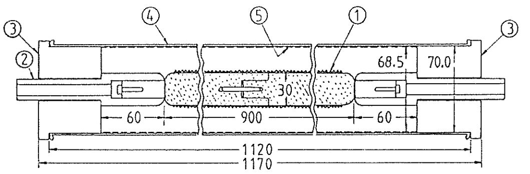


Fig. 1 Experimental circuit diagram of an ozone generator with a pulse power generator.



①; corona electrode ②; electrode supporter
③; insulator ④; glass cylinder
⑤; stainless steel wire mesh electrode

Fig. 2 Schematic diagram of a test ozone generator. (size in mm)

ohm, outer-diameter of inner-conductor of the feeder cable, $a=1.0$ and 1.5 mm, inner-diameter of outer-conductor of the feeder cable, $b=7.2$ and 9.3 mm, respectively, were used to couple the pulse power generator with the ozone generator tested.

Figure 2 shows a cross section of the test ozone generator. It consisted of an inner corona discharge rod, 30 mm in diameter and 90 cm long and made of a brass pyramid-project-embossed rod, and an outer grounded stainless steel cylinder. Three different types of outer cylinder, 56.5, 61.5, and 68.5 mm in diameter, were tested. And the largest outer cylinder was made particulary of a glass tube with a stainless steel mesh tube type electrode attached just inside of the glass tube, which makes it possible to see through the corona activities on the discharge electrode when it is operated. Many pyramid type projects were embossed on the corona discharge rod in shape with a base area of 2 mm × 2 mm and a height of 2 mm individually to concentrate the electric field on its tips and to produce intense, stable and restricted coronas for each pulse voltage occurred on its tips, which is one of very effective way to produce ozone.[8-10]

Figure 3 shows a feed air flow diagram consisted of a blower, a dryer using dry ice, a test

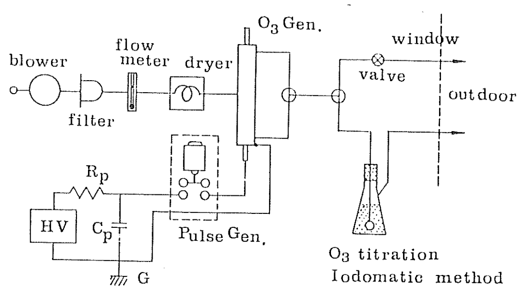


Fig. 3 Feed air flow diagram with a pulse generator.

ozone generator and an ozone monitor. The feed air from cool and clean outdoor was introduced at a flow rate of 4 l/min either directly or through the dryer. The uncontrolled outdoor air had a temperature, T, of 15 ± 3°C and a relative humidity, RH, of 50 ± 10%, and after cooling and drying, the resulting values were $T=0\sim10$°C, $RH=0\sim5$%, respectively.

The ozone concentration was monitored by chemical absorption and titration in potassium iodide solution.[7] The power consumption of the ozone generator was estimated from the discharge energy of the pulse forming capacitor and the peak pulse voltage across the pulse forming capacitor.

3. Experimental Results and Discussions

Figure 4 shows an effect of peak pulse voltage on the ozone generator. The generated ozone concentration increases with the applied peak pulse voltage reaching a maximum at about the peak pulse voltage of $V_p=56$ kV which represents an

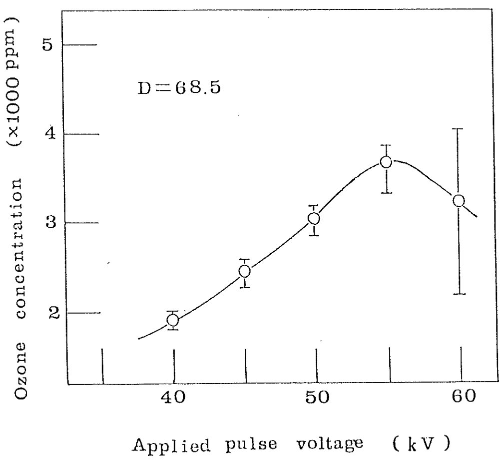


Fig. 4 Effect of peak pulse voltage on ozone generation.

optimum value for generating ozone effectively using this configuration. Above this maximum point of ozone concentration, the ozone concentration is fluctuated greatly, whose reason was found by observing the discharging activities through the glass tube electrode to be caused by the abnormal strong streamer coronas and arcings occurring on the corona points of the corona discharge rod, while intense and stable coronas were taking place at the all discharge tips with few archings at the point of maximum ozone concentration.

Figure 5 shows an influence of the value of the pulse forming capacitor, C_p, on ozone generation. The generated ozone concentration saturates to a certain value with the increase in C_p, while it was shown an abnormal resonating for the case of the helical strip-line type ozone generator.[6] The resonance occurring had been thought to be caused by having the large inductance component induced by its long and thin helical strip-line corona electrode wound on the insulator rod, which, however, had made an impedance matching problem of the ozone generator to the pulse power generator degrading the ozone generation efficiency greatly.[6] But for the case for the pyramid type ozone generator there was no resonance occurred, which represents that the inductance of the pyramid type corona electrode is negligible, whose details will be discussed later.

Figure 6 shows an effect of corona power, P_c, on ozone generation calculated from the values of C_p and V_p, $P_c=1/2\times C_p V_p^2$, across the pulse forming capacitor in the pulse power generator. It indicates that the ozone yield decreases with increase of corona power, while the ozone concentration increases with increase in C_p as shown in figure 5. The reason for the decrease of the ozone yield was thought to be caused due to the change of the effectiveness of corona discharge at the tips on the discharge electrode to the ozone generation, as described already in figure 4. It was shown through the glass tube electrode that when the corona power was small the discharges on the tips were looked like as a light blue ones while it was looked as a bright and arcing ones with sounds for higher corona power, this is, showing lower efficiency for generating ozone.[8]

Figure 7 shows an effect of the feed cable capacitance of 2 kinds of cable A and B on ozone generation. The normalized generated ozone concentration ratios of both cases of the cable A and B increase with increase of the capacitance of the feeder cable, having maximum values at about $C_c=75$ pF. Above those values of feed cable capacitance the concentration ratios decrease rapidly showing that there is an optimum value for the capacitance of the feeder cable for generating ozone effectively using this configuration.

The reason of having the maximum value of ozone concentration at this point was considered in detail. Figure 8 shows an equivalent circuit of the experimental set-up illustrated in figures 1 and 2, which consisted of a DC high voltage part, ①, a ripple filtering part, ②, a rotating spark gap, ③, a feeder cable part, ④, and an ozone generator part, ⑤. The values of the inductance of the cable, L_c, and the ozone generator, L_o, the capacitance of the cable, C_c, and the ozone generator,

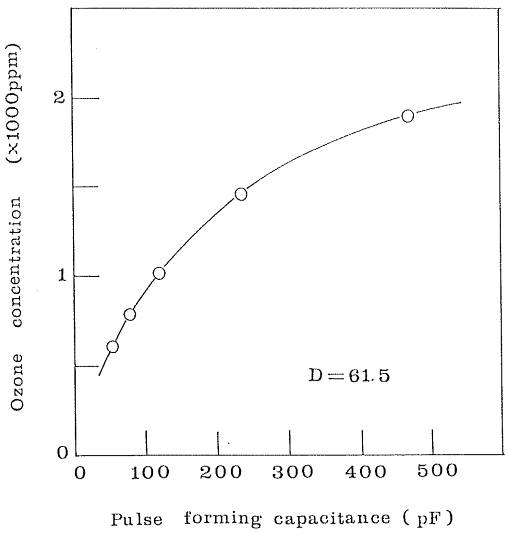


Fig. 5 Effect of pulse forming capacitance on ozone generation.

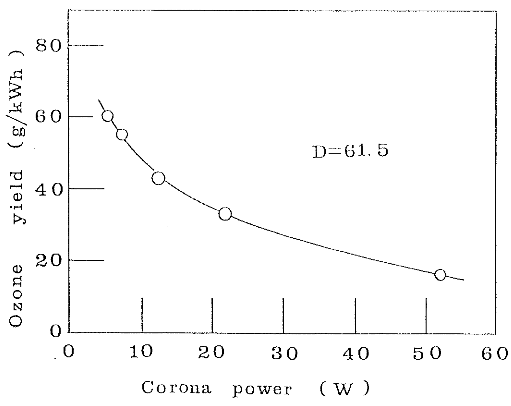


Fig. 6 Effect of corona power on ozone yield.

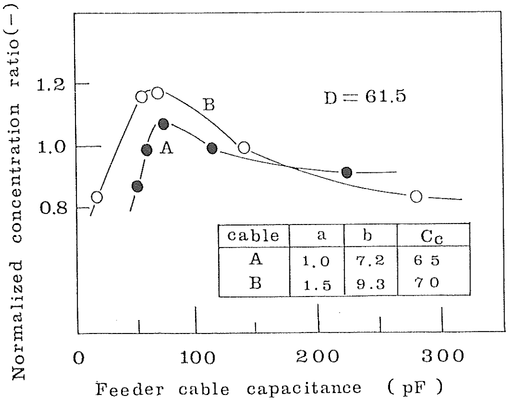
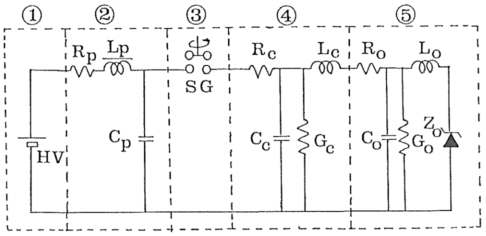


Fig. 7 Effect of feeder cable capacitance on ozone generation.



①; DC high voltage source ②; filter
③; spark gap ④; feeder cable
⑤; ozone generator

Fig. 8 Equivalent circuit of experimental set-up.

C_o were all calculated by the equation (1) from their real size, those were $L_c=0.39$ and $0.36\ \mu$H/m for the cable A and B, and, $L_o=0.15\ \mu$H/m for the ozone generator, $C_c=64$ and 69 pF/m for the cable A and B, $C_o=76$ pF for the ozone generator of $D=61.5$ mm, respectively, and

$$C=2\pi\varepsilon/\ln(b/a)$$
$$L=\mu\ln(b/a)/2\pi \qquad (1)$$
$$Z=[(r+j\omega L)/(G+j\omega C)]$$

the measured values of C_c and C_o by the LCR meter (YHP 4332A, Japan) were 65 and 70 pF/m for the cable A and B, and 84 pF for the ozone generator which showed about 10% different from the calculated value of 76 pF. The difference of 10% of C_o was found to be caused by the encounting only the effective corona discharge length of 90 cm long which ignored about 8 cm of real length of the supporting parts of both sides of the discharge electrode being hid in the insulator of both electrode supports (see figure 2). As the results shown in the figure 7, the maximum ozone concentration are obtained for both case of cable A and B at the feeder cable capacitance of about 75 pF whose values are just same as the capacitance of the ozone generator, 76 pF, that is, indicating the capacitance-dominant impedance matching condition, and showing only few effects of inductance of the cable and the ozone generator on ozone generation are acting in this present case of the pyramidally embossed rod type ozone generator.

For this type of configuration of an ozone generator, it had been found to effect greatly to ozone generation by the ratio of the projected corona tip height, h, to the interelectrode space of $(D\text{-}d)/2$, $2h/(D\text{-}d)$, which had been investigated already by author.[8,9] And so h had been determined as 2 mm for the present tested discharge electrode, which, however, had been thought to be optimum value for this purpose.[9,10] And the corona tip-to-tip distance, d_t, had also been one of important factors to influence generating ozone, since each of the corona tip needs a field controlling area to generate an intense and stable corona.[9,10] Figure 9 shows this effect of the projected corona tip-to-tip distance on ozone generation. The tip-to-tip distance were changed by means of covering the sharp tips of one line after one of the discharge electrode by taping with insulator ribbon materials in order not to generate coronas on them. As shown in figure 9, the normalized ozone concentrations are dependent greatly upon changing the corona tip-to-tip distance, reaching a maximum value of 1.2 times which was compared with that of the prototype one at $d_t=2$ mm. Above this point of d_t, the ozone concentration ratio decreases rapidly indicating that there is an optimum value of corona tip-to-tip distance for generating ozone effec-

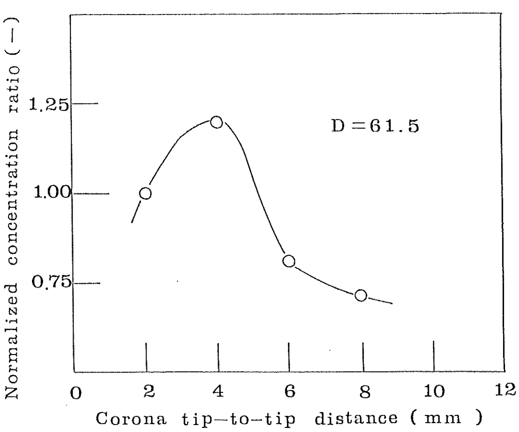


Fig. 9 Effect of corona tip-to-tip distance on ozone generation.

tively. This shows that each of the corona tip needs an area to generate an intense and stable corona, that is called, the Field Controlling Area as described above.[9,10]

Figure 10 shows an influence of the feed air flow rate on ozone generation plotted on a semi-log graph. The generated ozone concentration at the feed air flow rate range of 10–30 l/min decreases linearly with the increase of the feed air flow rate, while at the higher and lower value of this flow rate the concentration decreases and increases compared with the dotted line on the figure 10. It was thought to be caused at the higher feed air flow rate the cooling effect of the corona tips was higher, so the decomposition rate of the generated ozone in the ozone generation space was lower, while it was higher at the lower flow rate, which, however, has been known that a decomposition rate is depended greatly upon temperature in the ozone generating space.[11,12]

Figure 11 shows the ozone concentrations for 3 different diameters of the outer cylinder electrode of the ozone generator as a function of the pulse peak voltage when the cooled and dry air of a flow rate of 4 l/min was introduced. The generated ozone concentrations reach approximately 7370, 7700 and 7850 ppmv for the 3 different types of the outer cylinder diameters of 56.5, 61.5 and 68.5 mm respectively, which correspond to conversion efficiencies of 79, 77 and 80 g/kWh, those are about 1.3 times higher than that of a commercially available industrial ozone generator utilizing the silent electric discharge.[13] And it is thought that not only the ozone yield of the test ozone generator is higher but the potential to be developed is not also lower.

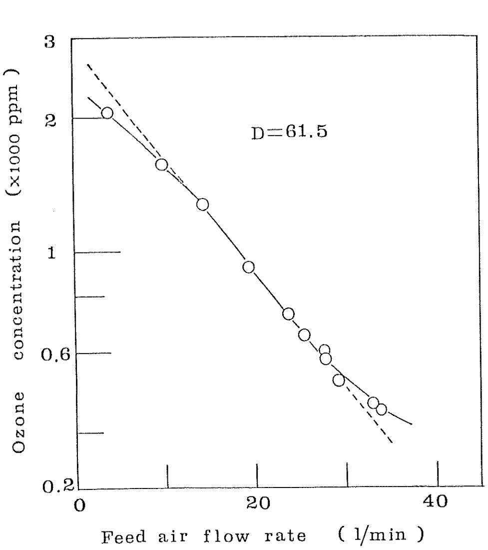


Fig. 10 Effect of feed air flow rate on ozone generation.

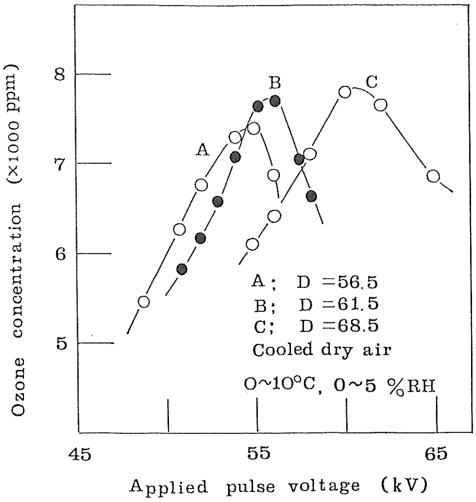


Fig. 11 Effect of peak pulse voltage and feed air cooling and drying on ozone generation.

4. Conclusions

The conversion efficiency and matching condition of an ozone generator can be significantly improved by modifying the discharge electrode of a helical strip-line discharge electrode of rod-to-cylinder type ozone generator to a pyramidally embossed rod type discharge electrode and by using a pulse corona discharge.

Parametric studies were carried out to obtain optimum values of peak pulse voltage and pulse forming capacitance of a pulse power generator, feeder cable and ozone generator capacitance, interelectrode spacing and corona tip-to-tip distance of the ozone generator, and, feed air flow rate and temperature.

The generated ozone concentration was very dependent upon the value of pulse forming capacitance, feeder cable and ozone generator capacitance, and corona tip-to-tip distance of the discharge electrode. Maximum conversion efficiencies and ozone concentrations were obtained with a pulse forming capacitance of about 500 pF, a same, matching capacitance of 75 pF of the feeder cable and the ozone generator, and, a corona tip-to-tip distance of 4 mm. When operated at optimum condition, ozone concentrations of 7370, 7700, and 7850 ppmv, which, however, corresponds to ozone yields of 79, 77, and 80 g/kWh, for 3 different outer-electrode-diameter types of ozone generators were obtained, which are approximately 30% higher than that of a comparable industrial sillent electric discharge type ozone generator.

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