

Effect of Rotating Electrode

S. Gnapowski, H. Akiyama, S. Hamid R. Hosseini, and C. Yamabe

Abstract—A gold coated copper rotating electrode was used to eliminate surface oxidation effect. This study examined the effect of electrode rotation on the ozone generation process and showed that an ozonizer with an electrode rotating system might be a possible way to increase ozone-synthesis efficiency. Two new phenomena appeared during experiments with the rotating electrode. First was that ozone concentration increased to about two times higher than that of the case with no rotation. Second, input power and discharge area were found to increase with the rotation speed. Both ozone concentration and ozone production efficiency improved in the case of rotating electrode compared to the case with a non-rotating electrode. One possible reason for this was the increase in discharge length of micro-discharges during electrode rotation. The rotating electrode decreased onset voltage, while reactor capacitance increased with rotation. Use of a rotating-type electrode allowed earlier observation of the ozone zero phenomena compared with a non-rotating electrode because, during rotation, the entire electrode surface was functional, allowing nitrogen on the electrode surface to be evenly consumed. Nitrogen demand increased with increasing rotation speed.

Keywords—Rotating electrode, input power, onset voltage, discharge canal.

I. INTRODUCTION

INCREASING the efficiency of plasma production and of plasma applications requires knowledge of what phenomena determine these factors. Important parameters such as the dielectric constant, its thickness, gap distance and surface condition of electrode influence efficiency [1]-[3]. Other parameters such as electrode configuration, the applied voltage waveform and the cooling system for the discharge region have also been studied [4]-[6]. An additional method for increasing efficiency is the rotating electrode reactor. Electrode rotation leads to the appearance of several new phenomena which caused an increase in ozone concentration in our experimental case. This paper describes characteristics of a dielectric barrier discharge (DBD) type ozonizer using a rotating type of electrode. Changes in the shape and length of discharge canals are investigated. An increase in rotation speed leads to such phenomena as increases in input power, reactor capacitance, and nitrogen demand as well as a decrease in onset voltage.

Use of a rotating-type electrode allowed earlier observation of the ozone zero phenomena compared with a non-rotating electrode because, during rotation, the entire electrode surface was functional, allowing nitrogen on the electrode surface to be

evenly consumed [7], [8]. Conditions for ozone concentration were different even constant input power. Ozonizers utilizing rotating electrodes produce quite different results from those using non-rotating electrodes [9]-[11]; for example, micro-discharge is not in the same position during experiment, and the entire electrode surface functions during ozone phenomena [12], [13].

II. EXPERIMENTAL APPARATUS AND PROCEDURES

A discharge reactor and nitrogen addition are shown in Fig. 1. The rotating electrode was coated with gold and high voltage was applied on it. The speed of the rotating electrode was varied from 0 to 800rpm by a variable speed motor. The dielectric barrier covered by a mesh electrode was a glass tube of length 110mm, diameter 15mm and its thickness was 1.25 mm. The outer mesh electrode made from copper wires with diameter of 0.1mm was grounded.



Fig. 1 Reactor

The size of the copper mesh electrode was 0.2mm square. 99.5% oxygen gas regulated by a digital mass flow controller was fed at a gas flow rate ranging from 0.5l/min to 2l/min. The purity of using nitrogen was 99.9% and his flow was controlled by digital mass flow controller. Applied voltage and its frequency were set at 9-10kV and about 12 kHz, respectively. Fig. 2 shows schematic diagram of our ozonizer. The discharge gap distance was 1.1mm and the discharge length along the reactor was 100mm. The gas temperature at the outlet of the ozonizer was measured during the experiments. The measured data was saved every day in a computer. All experiments were carried out at atmospheric pressure in oxygen at around room temperature (15~30°C).

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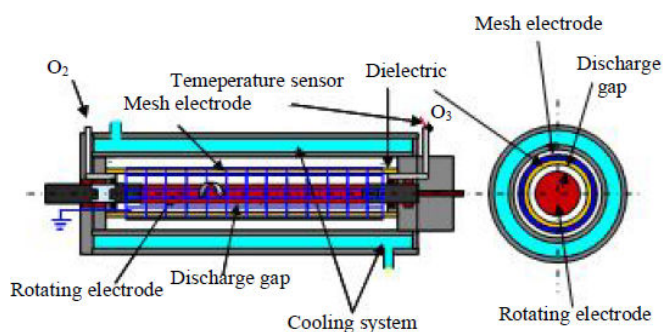


Fig. 2 Schematic diagram of ozonizer with rotating electrode

The current and voltage signals were processed by a digitizing oscilloscope Tektronix TDS 520A (2 channels, 500 MHz, 500 MS/s) and the voltage at the reactor was measured by a high voltage probe Tektronix P6015A. The discharge current through the coaxial electrode was measured using a Rogowski coil (MODEL 8585C, voltage pre ampere Pearson current monitor, Pearson Electronics, Inc., Palo Alto, CA, USA) and by capacitor divider (capacitor 1pF) was measured too. The ozone concentration was measured by the Ozone Monitor (EBARA JITSUGYO CO., Ltd: Type EG- 500). The cooling system is very important because an increase in temperature decomposes the produced ozone. In our case cooling water temperature was 10°C.

III. EFFECT OF ROTATING ELECTRODE

When the rotation speed rises, the input power increases with rotation speed as shown in Fig. 3. The rise of the rotation speed changes the input power, which increases with rotation speed. Fig. 3 shows the relationship between the rotation speed and the discharge power with Lissajous. During this experiment the gas flow rate was 0.5 l/min and the applied voltage was constant at 10 kV (peak – to – peak).

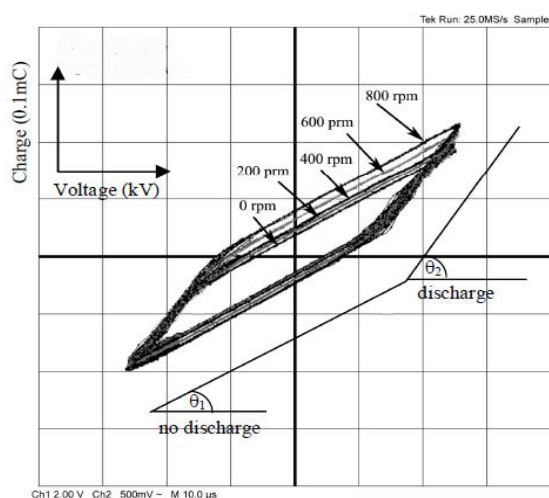


Fig. 3 Lissajous figure vs. rotation speed and two lines showing changes in capacitance

Fig. 3 shows the Lissajous figure from 0rpm (smallest figure) to 800rpm (the biggest Lissajous figure area). Was calculated the input power to be 4.59 W (0rpm), 5.5 W (200 rpm), 6.56 W (600rpm) and 6.73 W (800rpm). An increase of about 20 % at 200 rpm rotation speed and about 47 % at 800 rpm were confirmed. The change of capacitance during increasing rotation speed was observed. Fig. 4 shows the calculation and the change of capacitance and input power.

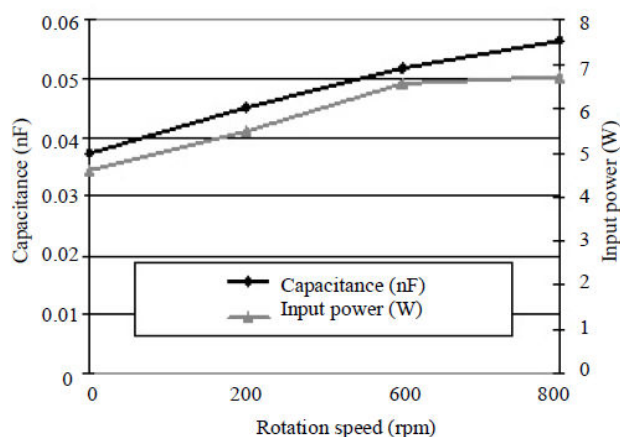


Fig. 4 The change of capacitances and input power vs. rotating speed at initial voltage of 10 kV in oxygen

Were calculated two capacitances, that is, the dielectric's capacitance and the gaseous space capacitance. The observed capacitance closely matched the predicted capacitance. The big angle showed capacitance when the dielectrode was discharging.

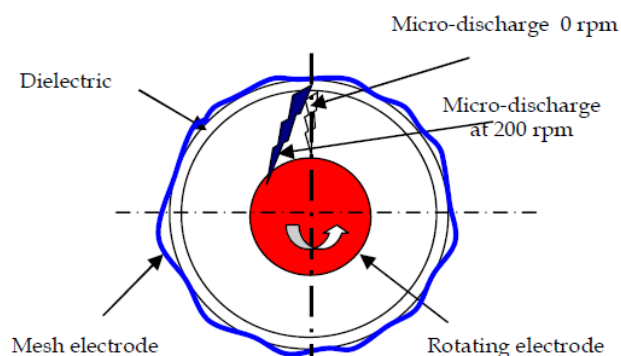
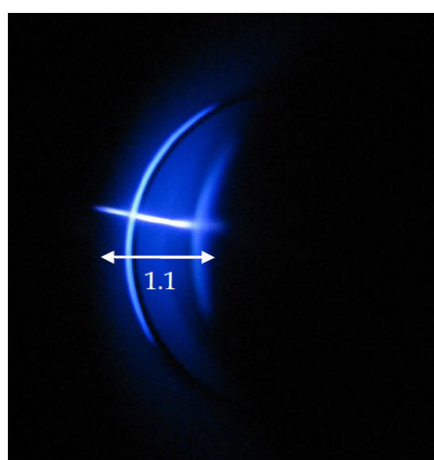


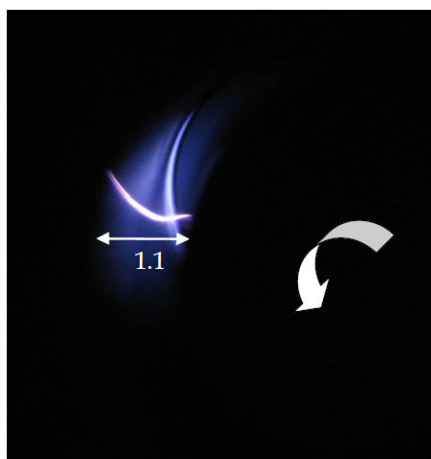
Fig. 5 Cross section reactor and micro-discharges without rotation

It was not matched well initially but gradually closed to the dielectrode's capacitance when the inner metal electrode increased its speed of rotation. Capacitance increased about 51 % at 800 rpm compare to the case with non rotation. This result is shown in Fig. 4. The capacitance increased during rotation, because it was observed that the discharge area became larger and more homogeneous. Another reason is change in micro-discharge shape (Figs. 6 (a) and (b)). Without rotation micro-discharges go through dielectric straight (1.25mm) but

with increasing rotation speed micro-discharge change dielectric crossing angle, and thickness is up to 1.25 mm. Capacitance of rotating electrode increased 51% compare to non rotating electrode and input power increased 47%. It is similar value. Fig. 4 shows the input power as a function the rotation speed of inner electrode at the oxygen gas flow rate of 1l/min. During the experiments, changes in discharge area and micro-discharge with rotation speed were visually observed. Therefore, the discharge canals should have been changed during rotation. In addition, it should be understood why ozone concentration increases during experiments with rotating electrodes. Generally in the case of non rotation micro-discharges are straight (i.e. perpendicular to the electrodes) and their length is the same as the discharge gap distance.



(a)



(b)

Fig. 6 (a) Micro-discharge without rotation (unit: mm), (b) Micro-discharge with rotation at 200rpm (unit: mm)

These phenomena are shown in the drawing in Fig. 5 in which the micro discharge with rotating electrode is also included.

When was changed our electrode and the gas supply was observed and took clearer photographs of single micro

discharge. The mesh copper electrode was changed to spring wire electrode (wire diameter of 1.6mm and pitch of 5mm) as well as the gas supply from oxygen to nitrogen. The discharge length of micro-discharges observed visually becomes longer with the rotation speed. These circumstances are shown in Figs. 6 (a) and (b).

It was found that both the input power and discharge area became large because the micro-discharges became long due to the rotating electrode. The micro-discharge looks like an arc. Figs. 6 (a) and (b) show the different situations of discharge (i.e. the difference in the length of micro-discharges) between non rotation and rotating (200rpm) electrodes. Fig. 6 (a) shows the micro-discharge without rotation. The micro-discharge was straight and its length was the same as the gap distance of 1.1mm. The micro-discharge became longer with rotation and as shown in Fig. 6 (b), at rotating speed of 200rpm, micro-discharge became 10% longer. The micro-discharge changed shape and became like an arc due to the rotation. The gas pressure changed and gas flow was not straight but around the surface of the electrode like a screw. When rotation speed faster than 200rpm was used the micro-discharges changed so fast and it was impossible to take clear photographs using standard camera.

On the other hand, the discharge area became more intensive and the ozone concentration increased with rotation (rotation speed at 200rpm). During the experiments, the discharge density and ozone concentration increased. When the micro-discharges become longer during the rotation, it will be possible to generate more collisions and higher ozone concentration, which will also be expected to lead to higher efficiency of ozone generation [13], [14]. The maximum ozone generation efficiency of 71.5g/kWh was obtained at the rotation speed of 200rpm and oxygen flow rate of 0.5l/min. When rotation speed was increased further, input power increased and the water cooling system was not enough to cool the electrode and ozone efficiency didn't increased. The efficiency increased about 30 % when the rotation speed was used.

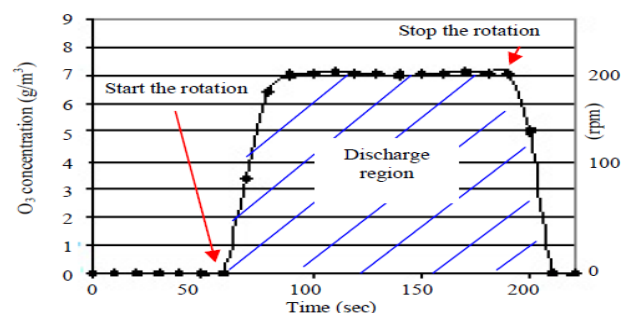


Fig. 7 Variation of ozone concentration for different rotation mode maximum rotating speed is 200 rpm

Fig. 7 shows another different phenomenon during the rotating of electrode. In this case, brass rotating electrode was used, the gas flow was 0.5l/min, applied voltage was 9 kV (peak – to – peak) and the frequency of about 12 kHz was used. Without rotation the discharge could not be observed, ozone

concentration would be zero and the discharge pulses using oscilloscope was not recognized.

When the rotation speed was increased up to 200rpm small pulses of discharge current were observed by oscilloscope and ozone concentration of about 7g/Nm^3 was measured. This experimental result shows that the rotation of the electrode decreases the discharge onset voltage. This phenomenon was also observed by using a different gas flow rate. Decrease in onset voltage appeared because gas pressure around surface of rotating electrode was changed by rotation. However, this phenomenon cannot be fully explained yet although the discharge current was measured by the current pick up coil to confirm the start of discharge.

IV. LONG TIME OPERATION

This experiment was run eight hours each day. During experiment, a computer was used to save our data. 99.5% oxygen was used. Its flow was regulated by a digital mass flow controller and was 0.5l/min . Voltage was set at 9.5 kV . A cooling water system was used. The rotation speed was constant during this experiment, at 600rpm , and a gold coated copper rotating electrode was used. This gold electrode was used for a few months before the long time operation but not continuously (without opening reactor and addition of nitrogen).

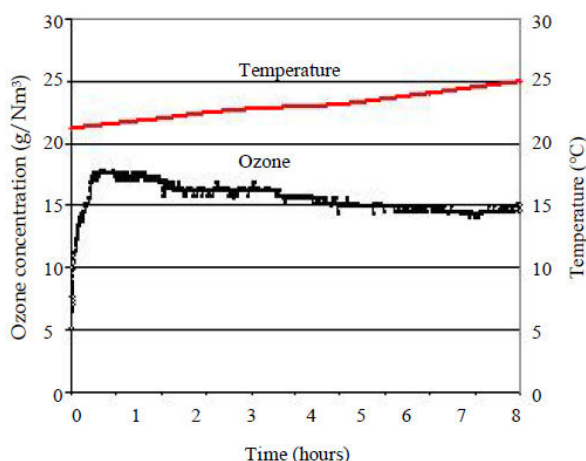


Fig. 8 The ozone concentration (New electrode)

A few times per month the reactor was opened and the surface of the electrode had contact with air (especially with nitrogen). After this, the long time operation would start. The first ozone zero phenomenon was observed after four weeks of continuous operation. Continuous operation means that the reactor was not opened and nitrogen was not added. The reactor was operated eight hours each day and ozone concentration gradually decreased with experiment time. As shown in Fig. 8, this was caused by an increase in temperature and a decrease of nitrogen on the surface electrode. Outlet gas temperature was measured. The ozone concentration was kept at a constant level (without fluctuation) during experiments with the new electrode. The same conditions were observed on the surface of the electrode for a few days and when nitrogen density

decreased, the ozone concentration data changed dramatically. After three weeks ozone concentration fluctuated between $7 - 0\text{ g/m}^3$ as is shown in Fig. 9.

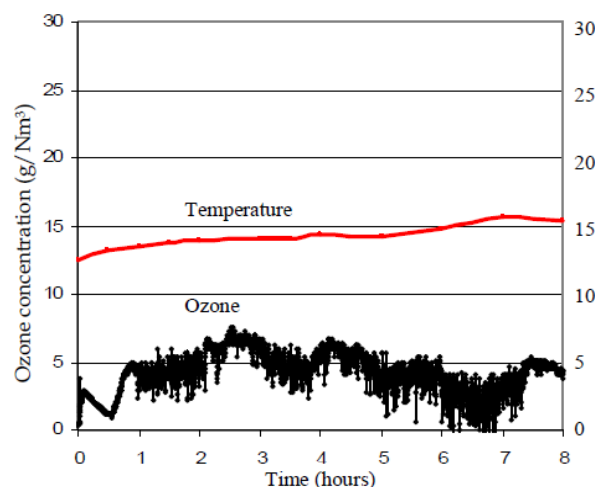


Fig. 9 Ozone concentration after few days experiments

This was observed for about one week and when nitrogen decreased dramatically, ozone production stopped.

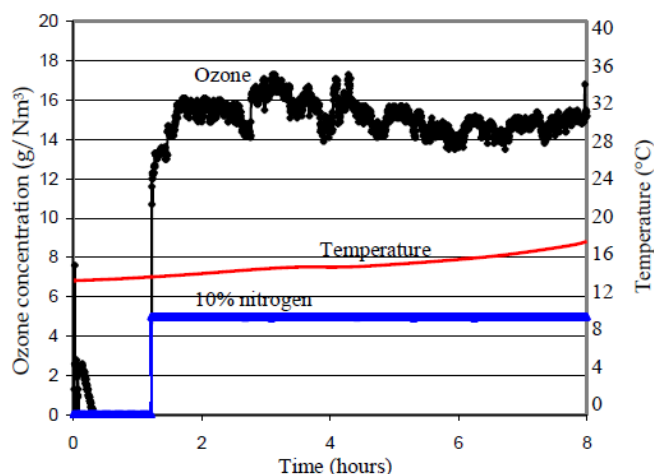


Fig. 10 Ozone zero phenomena

This zero ozone concentration was kept for about one hour before 10% nitrogen was added continuously as is shown in Fig. 10. A few seconds after mixing the gas ozone concentration rose again. Expanded addition 10% nitrogen shows Fig. 11.

The outlet gas temperature increased about 5 degrees C during experiments. Fig. 12 shows Lissajous figures. The Figure shows voltage and current during zero ozone concentration and at 15g/m^3 ozone generation. Input power during ozone zero phenomenon and at 15 g/m^3 ozone generation was similar.

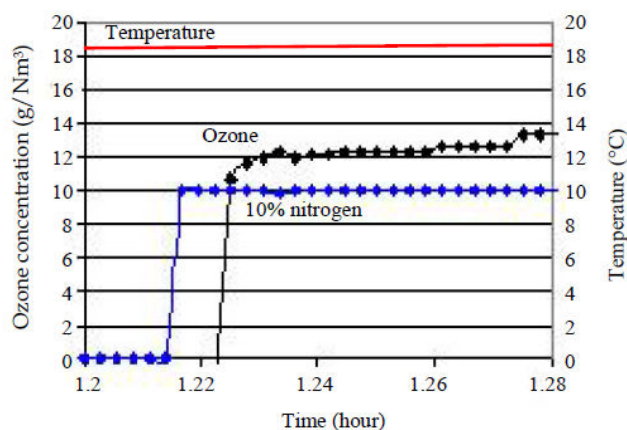


Fig. 11 Expanded addition 10% nitrogen during 600rpm operation

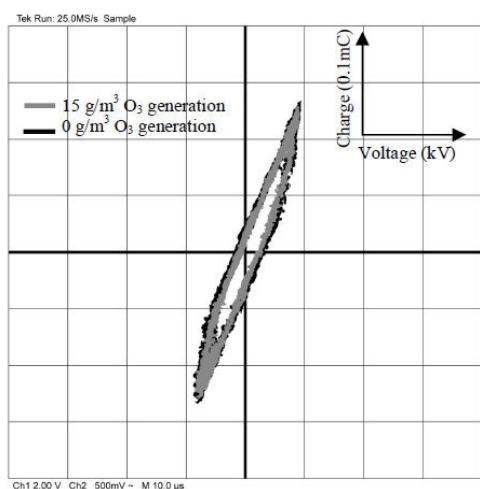


Fig. 12 Lissajous figure during zero ozone production and after mixing gas (15g/m³)

According to this data not only input power is important during ozone production but surface conditions also play very important roles. Discharge density was similar but the ozone generation completely different.

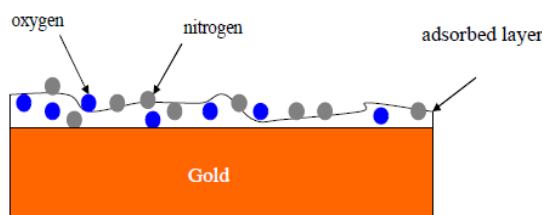


Fig. 13 Schematic surface electrode

Fig. 11 is showing expanded nitrogen addition time. After 30 seconds the ozone concentration was generated. About six half hours 15g/m³ was measured. The ozone concentration became more stabilize compare with previous days [15]. Fig. 14 shows data during 600rpm operation speed. After 15 minutes, ozone concentration decreased from 4g/m³ to 0g/m³. This was due to decreasing nitrogen density on the surface of the electrode [16],

[17]. Was kept conditions the same for about 30 minutes and when 10% nitrogen was added, ozone concentration increased to 16g/m³ and was kept constant at this level. When gas mixing was stopped ozone concentration increased to about 24g/m³. This showed that 10% nitrogen was too much and that the gas space of oxygen radical was decreased by nitrogen making it impossible to produce higher ozone concentration efficiently.

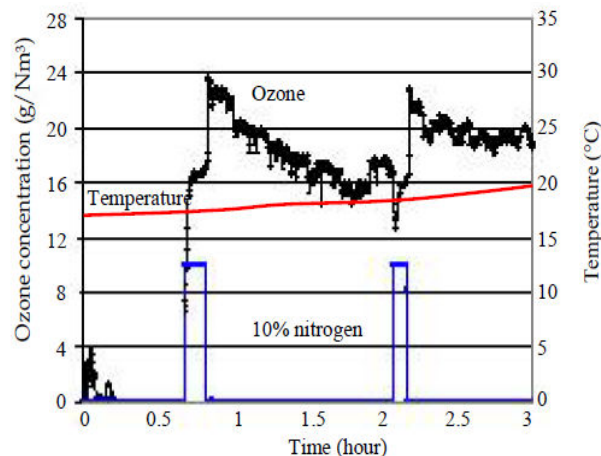


Fig. 14 10% Nitrogen addition during 600rpm operation

Ozone concentration after mixing gases was about 6 times highest compared to at the start of the experiment. Nitrogen was mixed and added for 10 minutes. During the 10 minutes that nitrogen was added, condition on the surface of the electrode changed (adsorbed nitrogen) and ozone was produced for one hour and the same procedure was repeated.

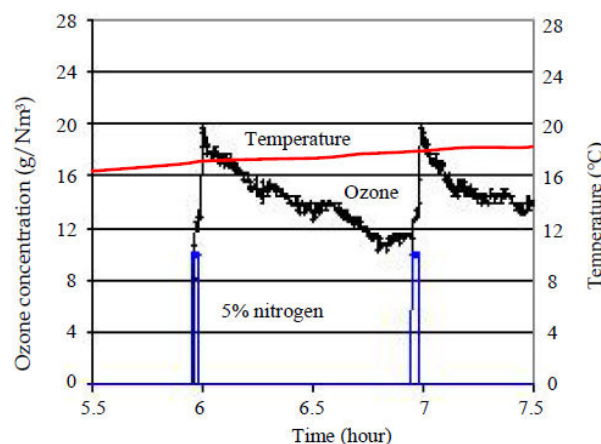


Fig. 15 5% Nitrogen addition without rotation

After the second nitrogen addition, the surface adsorbed more nitrogen and ozone concentration decreased slowly compare to the first addition. Input power and discharge density was same during different ozone generation. Fig. 13 shows a schematic figure about the surface of the electrode. Fig. 15 shows 5% nitrogen addition after ozone decreased to zero. This experiment was run without rotation and the same phenomena were observed. After gas mixing ozone production increased to

6g/m³. During mixing gases the ozone concentration could not increase further because there was too much nitrogen and the oxygen radicals reduced. This experiment shows different demand of nitrogen with and without rotating electrode. With rotating electrode nitrogen consumption increased about twice compared with non rotation.

During gas mixing ozone concentration was kept near 6 g/m³. According to our data after nitrogen was added ozone was produced again and nitrogen must be mixed at correct proportions. Without rotation 2–3% nitrogen is enough to produce highest ozone concentration and demand of nitrogen increases with increasing rpm and at 600rpm 6-7% nitrogen is the right proportion to mix with oxygen. Very important parameters during ozone generation were surface condition and nitrogen density at the adsorbed layer.

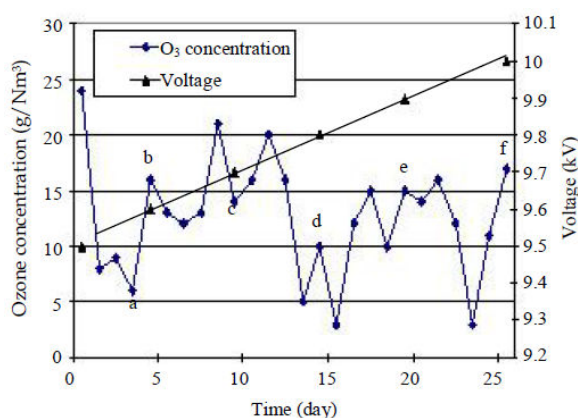


Fig. 16 Increasing onset voltage during long time operation and ozone concentration vs. day is also shown in the figure

During long operation time was observed increasing onset voltage. This was due to decreasing nitrogen density at the surface of the electrode. Fig. 16 shows our onset voltage data during a one month operation. Were observed a gradual increase in onset voltage every week by around 100 V. Nitrogen densities determine the onset voltage and ozone production. Using oscilloscope onset voltage was measured and voltage and current was observed.

- 1st addition of 10% nitrogen
- no addition of nitrogen
- addition of 5% nitrogen
- no addition of nitrogen
- no addition of nitrogen
- no addition of nitrogen

According to data (Fig. 15) without addition of nitrogen ozone concentration gradually decreased but onset voltage increased with decreasing nitrogen. Ozone concentration during these experiments fluctuated, if nitrogen was added ozone concentration automatically increased.

V. CONCLUSION

- Both the discharge power and ozone concentration were improved by using a rotating electrode. In case a rotating

electrode was used for the ozonizer different phenomena such as the increase of discharge area was observed compared to non rotation.

- Ozone concentration increased about two times higher with rotating electrode.
- The produced ozone increased with the rotating electrode speed and the efficiency of ozone production was improved by 30 % by rotation.
- The rotation of electrode decreased the discharge onset voltage.
- During rotation discharge area became more uniform.
- A difference in ozone generation was observed with same input power. Perhaps due to a decrease in nitrogen density on the surface of electrode.
- Ozone concentration became unstable when nitrogen density at the surface of the electrode decreased.
- Nitrogen consumption increases with increasing of rotation and was about two times more at 600 rpm compared with non rotation.
- Density of nitrogen influenced the discharge onset voltage.
- A very important parameter for the ozone generation is surface condition and nitrogen density at adsorbed layer.

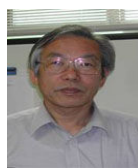
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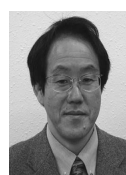
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