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THE EFFECT OF THE THIRD ELECTRODE ON THE OZONE GENERATION OF A WIRE-PLATE TYPE NONTHERMAL PLASMA REACTOR WITH A SLIT BARRIER

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ABSTRACT
The effect of the third electrode on the ozone generation of a wire-plate type nonthermal plasma reactor, with a slit barrier, has been investigated experimentally. When a third electrode is installed on the slit of the slit dielectric barrier, where the surface corona discharges occurred, it is found that a significantly increased ozone generation could be obtained for negative corona discharge. This, however, indicates that the third electrode can control the discharges, not only the corona-wire discharge but also the slit discharge on the barrier in the plasma reactor. As a result, a naked wire, which is used as a third electrode, significantly influences the fields of the corona wire and the surface charges. An insulator-wrapped wire also has a strong effect on the discharges. As a result, a high amount of the output ozone can be obtained with the third electrode of a naked wire of the open terminal case and an insulator-wrapped wire of a 20-Mohm-resistance, respectively

1. INTRODUCTION

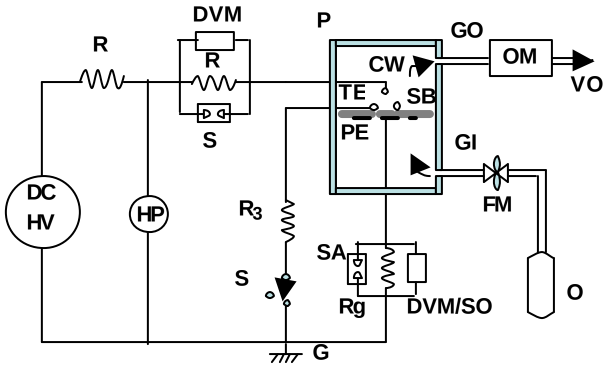
Air pollution is the most significantly environmental problems facing the world today. Non-thermal discharge plasma techniques offer an innovative approach to the cost-effective solution of these problems [1-4]. Several non-thermal discharge plasma techniques have been proposed for the removal of NOx, SOx, VOCs, and CFCs from pollutant gases [5]. These include the production of non-thermal discharge plasma using a pulsed corona discharge [1, 5, 6], a silent or dielectric barrier discharge [7], a surface discharge [8], an electron beam [5, 9] and a corona discharge in a ferroelectric pellet packed-bed [5, 10, 11]. The effective removal of NOx, SOx, and VOCs from pollutant gases, however, requires the generation of an intense corona discharge in the processing region of the plasma reactor [5]. Consequently, most of the electrical energy fed the reactor has to supply the production of energetic electrons instead of heating the ambient gases and ions in the processing space [5, 12]. The removal of pollutant gases can be stimulated by an electrophysicochemical reaction. This electrophysical reaction originates from the energetic electrons [9], where the electrochemical reaction is mainly caused by the ozone and radicals produced from corona discharge in a non-thermal discharge plasma reactor [5, 6]. Effective ozone generation is the key technology in making nonthermal plasma reactors practical and effective for removing pollutant gases [5, 6].

A wire-plate type plasma reactor, with a slit barrier, has been reported as an effective nonthermal plasma reactor because it produces ozone greatly [13, 14]. When a DC voltage is applied to the corona electrode of the wire-plate type plasma reactor with a slit barrier, which is installed on the ground plate electrode, the surface of the slit barrier become corona-charged, and a strong electric field is formed between the corona-charged surface and ground electrode, through the slit of the barrier. Thus, the slit and the surface of the barrier are covered with intense corona discharges. Due to the back current from the slit and the surface discharges flowing toward the corona wire in the wire-plate airgap spacing, the efficiency of the producing ozone would decrease.

In this paper, the effect of the third electrode on ozone generation of a wire-plate type nonthermal plasma reactor, with a slit barrier, is described. This proposed configuration has been investigated via experiments. This paper will report on the current-voltage and ozone generation characteristics of the plasma reactor, both with and without the third electrode. Parametric studies regarding the resistance and the airgap distance of the third electrode have been conducted, and their characteristics have been analyzed and compared for each case.

2. EXPERIMENTAL SETUP

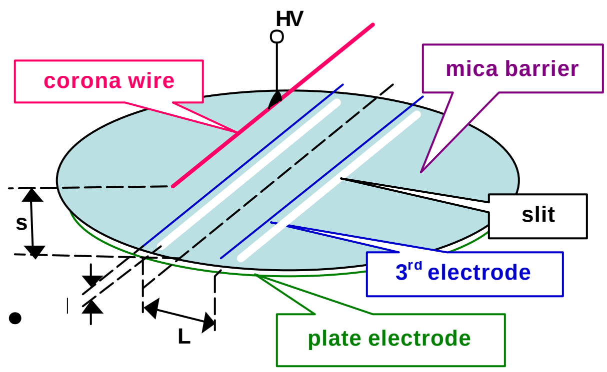
A schematic diagram of the experimental setup is shown in Fig. 1. The setup consists of a cylindrical non-thermal plasma reactor chamber (PR), a high-voltage DC power supply (DCHV), an O_2 gas feeder (OB) with flowmeter (FM), an ozone monitor (OM), and current and voltage measurement sets (HP, DVM, SO). The configuration of the reactor is a typical wire-plate type electrode system consisting of a corona wire electrode (CW) and a ground plate electrode (PE). A slit mica sheet barrier (SB) is installed on the ground electrode (PE). A third electrode (TE) is tested and installed on the slits of the mica barrier.



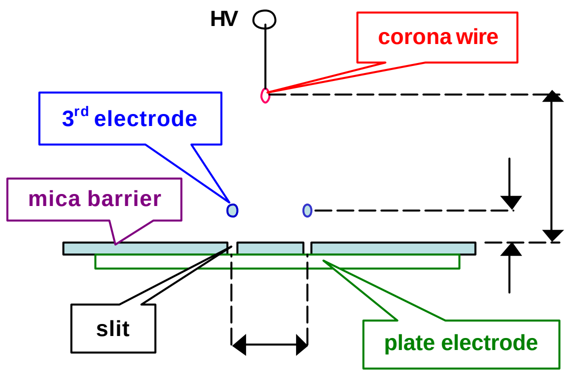
PR : plasma reactor	**CW : corona wire**	**PE : plate electrode**
TE : third electrode	**SB: slit dielectric barrier**	**DCHV : dc HV supply**
SA : surge arrestor	**R_3 : third electrode**	**Rp : protection resistor**
G : ground	**Rc,Rg, : shunt resistors**	**SW : rotary switch**
HP : HV prove	**DVM : digital voltmeter**	**SO : storage oscilloscope**
OB : oxygen bombe	**GI : gas inlet**	**GO : gas outlet**

Figure 1: A schematic diagram of the experimental setup.

Fig. 2 shows a closeup view of the reactor with a slit barrier and a third electrode. The corona electrode is a 0.18-mm in diameter and 8-cm long stainless steel wire. The ground electrode is an 8-cm diameter stainless steel meshed-plate. Two types of the third electrodes were tested, one electrode is a 0.18-mm in diameter and it has an 8-cm long stainless steel wire, and the other is a 0.50-mm outer-diameter and a 0.25-mm inner-diameter, and an 8-cm long Teflon-wrapped insulator wire. The third electrode was set on the slit with an airgap spacing *h* ranged between 0.0 and 2.0mm in this experiment. The dielectric barrier is a 9-mm diameter, 0.5-mm thick pressed mica sheet (e_r=5.0, p=3.5Tohm/?). There were two 0.3-mm scarred slits in the mica barrier. The slit-to-slit width was set at a constant value of 15.0mm, which is the same as the airgap spacing, so that a surface corona discharge can occur on the slit barrier. The airgap spacing *s* between the upper corona wire electrode and the bottom slit barrier is set at a constant value of 15.0mm. As a result, a spatial corona discharge can occur in the air gap.



(a) closeup configuration of the proposed plasma reactor



(b) sideview of the proposed plasma reactor

Figure 2: A configuration of the proposed plasma reactor with a slit barrier and a third electrode.

An adjustable, DC high voltage between 0 and 40kV was applied between the electrodes. The voltage was monitored using a Fluke 75 Digital Voltmeter (DVM) and Tektronix P6015A, 1000:1 high-voltage probe (HP), as shown in Fig. 1. The corona current was measured using a shunt resistor with a surge arrestor (SA) and a DVM. The high-voltage and corona-current waveforms were observed using a Tektronix TDS 340A Storage Oscilloscope (SO), as shown in Fig. 1. Oxygen gas (99.9% pure) is fed as the input gas via the input port (GI) of the reactor, at a constant flow rate of 1.0 l/min. The input gas is vented to the output port (GO). The amount of ozone concentration from the output port (GO) of the reactor was measured using an ozone monitor (OM, Dasibi DY 1500).

3. RESULTS AND DISCUSSION

Fig. 3 shows the measured current-voltage (I-V) characteristics, for three types of plasma reactor, the wire-plate type without SB and TE (here after WP), the wire-plate type with SB (here after WB), and the wire-plate type with SB and TE (here after WT). The corona characteristics of the WP exhibited a very slow increase and an eventual breakdown as the input voltage increased to above 21.0kV and 24.8 kV for the positive and negative corona, respectively. The I-V characteristics of the WB and WT were significantly different from those of the WP. In particular, the corona current increased more rapidly and with an increase of the input voltage, reaching peak corona currents of up to 1.38mA and 1.34mA at voltages of about 14.4 kV and 14.7 kV, respectively, for the negative and positive coronas of the WB, and to 1.39mA and 1.45mA at voltages of about 14.7 kV and 15.5 kV, respectively, for the negative and positive coronas of the WT.

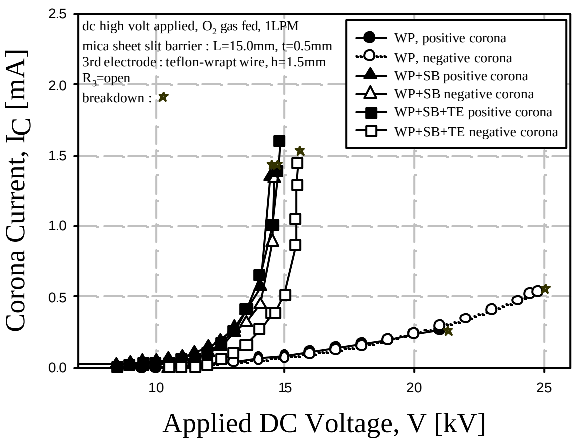


Figure 3: I-V characteristics of the three types of plasma reactors.

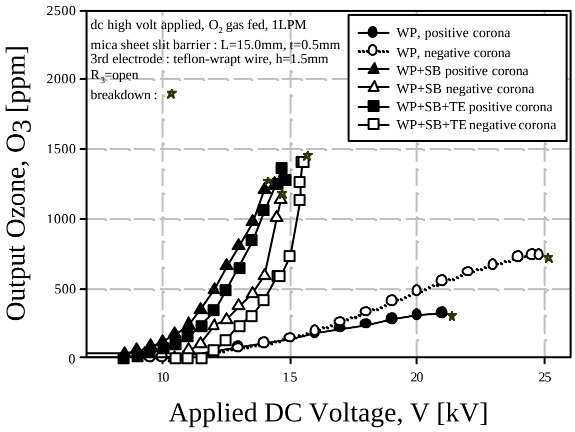
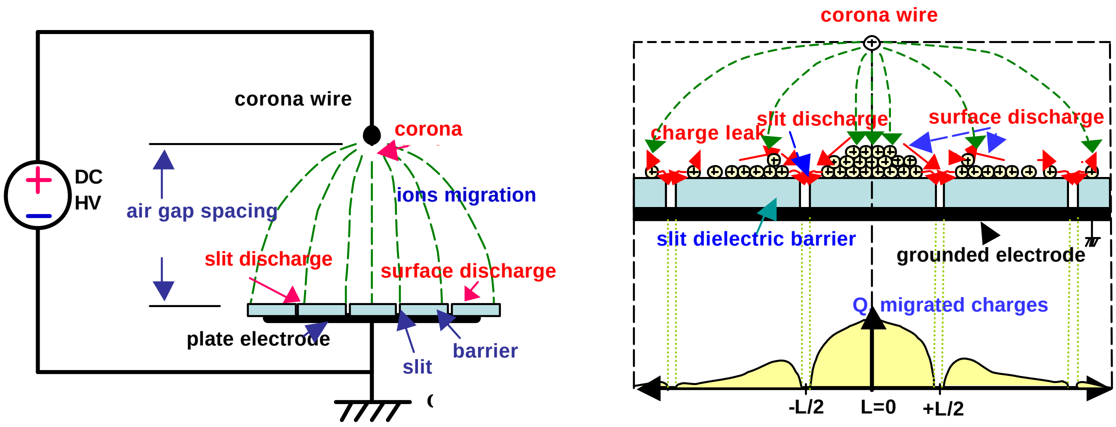


Figure 4: Ozone generation characteristics of the three types of plasma reactors.

Fig. 4 shows the output ozone generation characteristics, as a function of the applied DC high voltage, for the three types of plasma reactors, WP, WB and WT. As the plots show, the generation of ozone is initiated at the lower corona onset voltage and it increases with an increase in the input voltage, until a maximum value is reached near the breakdown voltage. Higher amounts of output ozone were produced from the plasma reactors, with maximum values of 1,244ppm and 1,130ppm from the WB and 1,364ppm and 1,414ppm from the WT, as compared with 318ppm and 741ppm from the WP, for the positive and the negative corona, respectively, as shown in Fig. 4 and Table 1.

The effect and action of the TE might be explained in the following way: As indicated in Fig. 5, when a corona discharge originates from the upper corona wire electrode, the ions that migrate toward the SB are attached to the surface of the SB. The charge relaxation time constant, given by $t=?e_0e_r$ =153s for mica sheet, is very long [11, 13, 14]. The charges that are deposited on the surface of the SB thus cannot be dissipated within a short time. If, however, there is a slit on the dielectric barrier, then the charges that are deposited on the surface of the SB can be discharged through the slit to the ground electrode rapidly, within a short time.

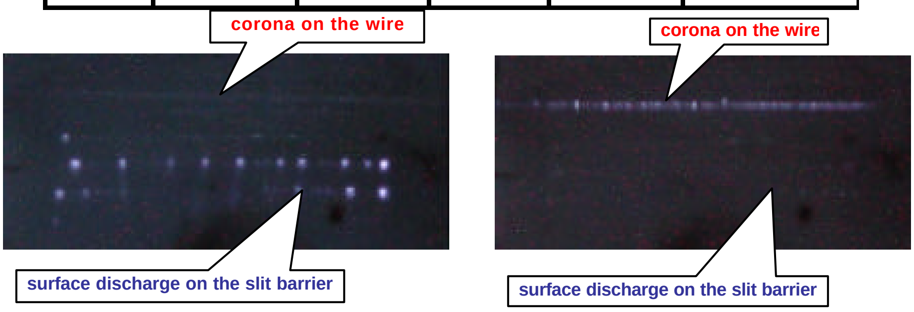


(a) schematic diagram *(b) corona discharge mechanism*

Figure 5: A schematic diagram and corona discharge mechanism of the wire-plate plasma reactor with a slit barrier.

Table 1. Comparisons of the characteristics of the three types of plasma reactors.

Plasma Reactor Types		Vam [kV]	Icm [mA]	O_3m [ppm]	O_3m/O_3WP [-]
Positive corona	WP	21.0	0.27	318	1.00
	WP+SB	14.4	1.38	1,244	3.91
	WP+SB+TE	14.7	1.39	1364	4.29
Negative corona	WP	24.8	0.52	741	1.00
	WP+SB	14.7	1.34	1,130	1.52
	WP+SB+TE	15.5	1.45	1414	1.91



(a) positive corona discharge (b) negative corona discharge

Figure 6: Photographs of the corona discharges on the wire and slit barrier.

As a result, intense surface micro-discharges occur [13-15], as shown in Fig. 6. As a result, the corona current and the ozone generation of the WB can be greatly increased, as indicated in Figs. 3, 4 and Table 1.

These results are attributable to the intense micro-discharges that occur dominantly in the slits of the barrier, as show in Fig. 6. A third electrode is installed near the slit, where the corona discharges occurred. The third electrode performs two controlling actions; a field enhancing action and an ion-reducing action. These actions are able to control the discharges, which might increase the corona wire current and decrease the back-current ions from the discharges on the slit barrier. This is shown in Fig. 4 and Table 1. In this paper, we conducted an experiment in order to investigate the effect of the third electrode on the ozone generation of the wire-plate plasma reactor, with a slit barrier.

There is space potential in a wire-plate, air-gap space, where a high voltage is applied. The space-potential distribution would be in proportion to the distance from the corona wire, where is greatly strong, to a ground electrode, where is very weak [16]. If there is a third electrode between the corona wire and the ground electrode, the potential of the third electrode might have an influence on the field to corona wire.

When a slit barrier is set under the third electrode, the surface discharge on the barrier also influences the third electrode. This means that the potential of the third electrode could influence both fields, the corona wire field and the surface charge field. These would increase the corona-wire current and decrease the back-current from the surface discharge of the slit barrier. The third electrode can be set at a proper value for its potential. It controls the fields, produces a better corona discharge, and generates a higher output ozone.

The space-potential of a given space-point is determined by the distance from the ground electrode, *h*, and a grounded third resistance, R_3. The smaller values of *h* and R_3 give lower potentials, while larger values of *h* and R_3 form higher potentials.

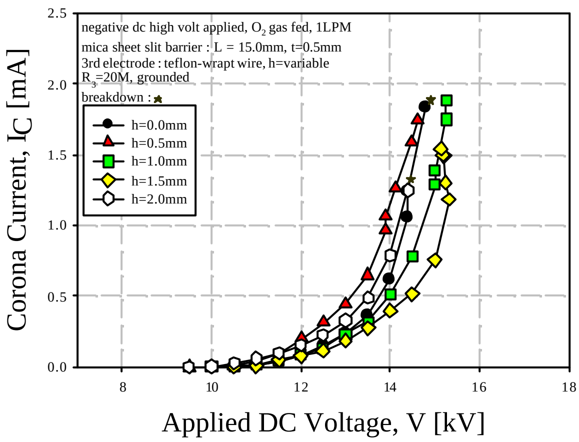


Figure 7: I-V-h characteristics of the proposed plasma reactor.

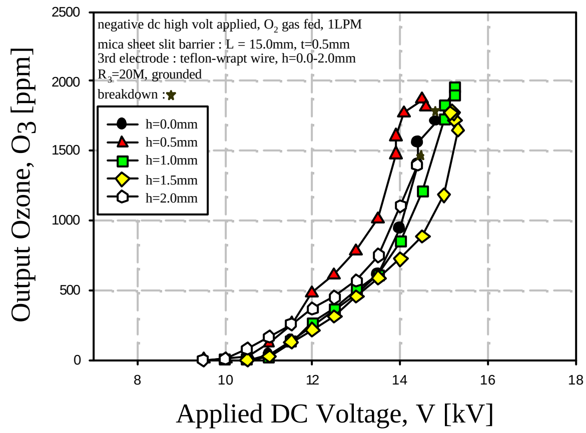


Figure 8: O_3-V-h characteristics of the proposed plasma reactor

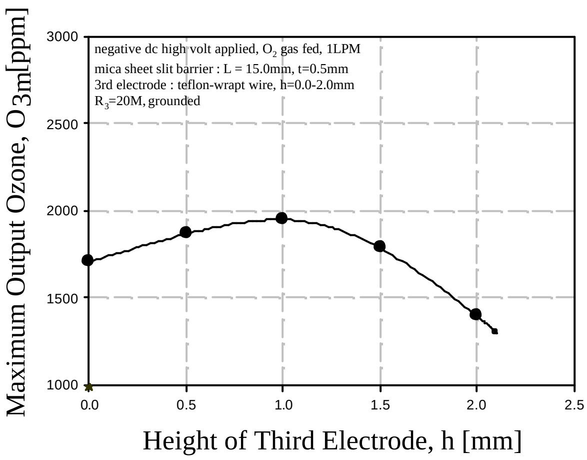


Figure 9: O_3-h characteristics of the proposed plasma reactor

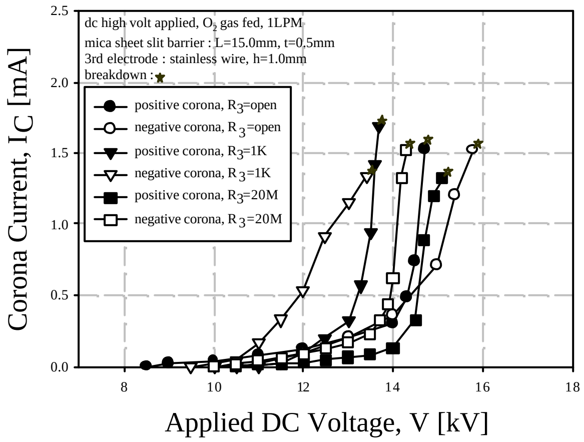


Figure 10: I-V-R_3 characteristics of the proposed plasma reactor

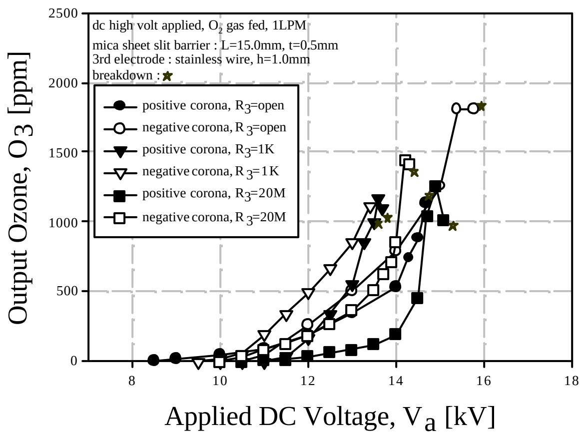


Figure 11: R_3-V-R_3 characteristics of the proposed plasma reactor

Figs. 7 and 8 show I-V and ozone generation characteristics of TE for different ranges of h=0.0~2.0mm at the fixed R_3 of 20Mohm. As shown in Figs.7 and 8, *h* influenced significantly by the corona current and ozone generation. Fig. 9 shows that there is an optimum value of *h*, *h*=1.0mm, where by it can control fields properly, produce a better corona discharge, and obtain higher output ozone.

Figs. 10 and 11 show the I-V and ozone generation characteristics of the WP, WB and WT for different grounded, third resistance (R_3) levels, 1kohm, 20Mohm and an open case (R_3 infinite), at a fixed amount of *h*=1.0mm. As shown in Figs. 9 and 10, R_3 had a significant influence greatly on the corona current and ozone generation, particularly for the negative corona.

Table 2 shows the comparisons for the three types of plasma reactors, WP, WB (WP+SB) and WT (WP+SB+TE) with regard to the positive and negative corona discharges. For the wire-plate (WP), the maximum measured ozone concentration amounts were only 318ppm and 741ppm for the positive and negative corona, respectively. For the wire-plate with a slit barrier (WB), the maximum ozone concentrations levels increased to 1,244ppm and 1,130ppm for the positive and negative corona, respectively. With the WB of the third electrode (WT), the maximum ozo ne concentration amounts increased significantly to 1,809ppm and 1,948ppm particularly for the negative corona, respectively. The output ozone concentration levels of the WT (WP+SB+TE), at optimized *h* and R_3, were 1.60 and 1.72 times higher then those of the WB especially for the negative corona discharges.

The reason for this comes from Fig. 6, which shows that there is a dominantly intense corona discharge from the corona wire for the negative case, while a surface discharge actively occurs on the slit barrier for the positive case. In this experiment, the third electrode was set near the slit barrier accordingly it might have a significant influence on the surface discharges of the slit barrier more than that of the upper corona wire. The surface discharge would be stimulated by the third electrode ~~to~~ and become intensified, thus producing additional ozone.

Table 2. An evaluation of the characteristics of the proposed plasma reactor.

Plasma Reactor Types & Experimental Conditions				Vam [kV]	Icm [mA]	O_3m [ppm]	O_3m/O_3WB [-]
Positive Corona	WB (WP+SB)			14.4	1.38	1,244	1.00
	WT (WB+TE)	Naked Wire	R3=1KO	13,6	1.42	1,163	0.93
			R3=20MO	14.9	1.20	1,251	1.01
			R3=8 O	14.7	1.53	1,130	0.91
		Teflon Wrapped Wire	R3=1KO	15.4	1.16	1,183	0.95
			R3=20MO	15.1	1.39	1,209	0.97
			R3=8 O	15.2	1.52	1,212	0.97
Negative Corona	WB (WP+SB)			14.7	1.34	1,130	1.00
	WT (WB+TE)	Naked Wire	R3=1KO	13.4	1.34	1,114	0.98
			R3=20MO	14.2	1.33	1,437	1.27
			R3=8 O	15.8	1.52	1,809	1.60
		Teflon Wrapped Wire	R3=1KO	14.4	1.47	1,685	1.49
			R3=20MO	14.7	1.62	1,948	1.72
			R3=8 O	14.4	1.05	1,313	1.16

A naked wire is used as a grounded third electrode, and then fields from the corona wire and the surface charges will influence greatly, while an insulator-wrapped wire will have little effect on the fields. As shown in Table 2, high amounts of an output ozone, 1,809ppm and 1,948ppm, can be obtained as the optimum conditions for a naked wire on an open case (R_3 infinite), and the insulator-wrapping for a wire R_3=20Mohm, whereby *h*=1.0mm, respectively.

This result is attributable to the intense micro-discharges that occur at the slits and surfaces of the barrier, which, can be controlled by the actions of a grounded TE.

From the results, the third electrode of a wire-plate type plasma reactor with a slit barrier can control the corona discharge discharges, the corona wire discharge and the surface discharges of the slit barrier. The wire-plate type plasma reactor with a slit barrier, by installing a third electrode on the slit barrier, may be of use as an effective plasma reactor that can remove pollutants.

4. CONCLUSION

In this paper, a new wire-plate type of discharge plasma reactor, with a mica slit barrier and a third electrode, has been investigated experimentally. It is focused on the effect of the third electrode on ozone generation in order to enhance the ozone generation efficiency of the plasma reactor. The following conclusions have been made:

From the observed results, the third electrode of a wire-plate type plasma reactor, with a slit barrier, can control the corona discharges of the corona wire electrode and the surface of the slit barrier. Then the third electrode controls the fields, forms a better corona discharge, and produces a higher output ozone.

A naked wire, which is used as a grounded third electrode, has significant influence on the discharges of the corona wire and the surface charges. In addition, an insulator-wrapped wire also has an effect on the fields. As a result, high output ozone levels, 1,809ppm and 1948ppm, can be obtained as the optimum conditions for the naked wire of the open terminal case (R_3 infinite) and for the insulator-wrapped wire of R_3=20Mohm, at a fixed *h*=1.0mm, respectively.

It is found that this type of plasma reactor with a slit barrier and a third electrode may be an effective as a plasma reactor for the removal of pollutant gases.

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