International Journal on Advanced Science Engineering Information Technology

Vol.8 (2018) No. 4
ISSN: 2088-5334

Development of an Electrostatic Air Filtration System Using Fuzzy Logic Control

Dewi Nurhaji Meivita[#1], Muhammad Rivai[#2], Astria Nur Irfansyah[#3]

[#]Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, Indonesia
[1]dewinurhajimeivita95@gmail.com; [2]muhammad_rivai@ee.its.ac.id; [3]irfansyah@ee.its.ac.id

***Abstract*— Particulate matter is one of the factors that can affect air quality. The air quality can be determined by the Air Pollution Index, which has several parameters including PM_{10} and ozone (O_3). Air pollution can be overcome by using a filtration system based on electrostatic precipitation when particles are attached to the static charges. In this study, we have developed a prototype of the electrostatic filter based on fuzzy logic control to reduce air pollution of particulate matters. The electrostatic filter is an ozone generator consisting of plate-type corona discharge and a high voltage dc generator. The experimental results showed that the more ozone generators used as electrostatic filters, the faster the particulate concentration decreases. However, the use of ozone generators may increase the concentration of ozone in the air that can be harmful to human health. Therefore, we have developed an electrostatic precipitation-based air pollution control using fuzzy logic. Semiconductor gas sensor and laser dust sensor are used as feedback signals for the system in regulating the number of charges released by ozone generators. Implementation of this control system can reduce the particulates of PM_{10} by 80% within 10 minutes while maintaining a low level of ozone during the air purification process.**

***Keywords*— air pollution; electrostatic filter; fuzzy logic; ozone generator.**

I. INTRODUCTION

Industrial developments and the increasing number of fossil fuels vehicles have become the largest contributors to air pollution due to combustion flue gas. Air pollution is a threat to human health, particularly in the metropolitan area throughout the country. However, the impact of traffic activity may increase the amount of particulate matter (PM) emission and flue gas emissions [1], [2]. PM is a widespread air pollutant. Exposure to fine particles can cause short-term health effects, especially lung function [1]. Increased concentration of PM becomes the most important factor in air quality problems. PMs are particles derived from all types of combustion. Particulates are grouped by the sizes into PM0.1 which has a diameter of less than 0.1µm, PM2.5 has a size of less than 2.5µm, and PM10 has a size of less than 10µm [3]. According to the Department of Environment and Natural Resources (DENR), the Total Suspended Particles (TSP) are just PM2.5 and PM10 [1].

Technological developments in the environmental field have result in much research to reduce particulate levels in the air. Particulate Wet Scrubber technique can remove the PM with a diameter of less than 0.3µm, but this technique produces liquid waste. Another method used to reduce particulates is by utilizing the static electrical properties of charged particles called an electrostatic filter. In this method, the corona discharge technology is used as an electrostatic filtration or Electrostatic Precipitator (ESP). When the gas passes between two electrodes with a voltage of about 10 kV, the barrier discharge will occur when the gas is partially ionized and produces a violet light [4]. An ESP uses a plate-type corona discharge connected to a high voltage dc using two cables mounted on the electrode part and the ground metallic plate part. The ground electrode side is faced onto a plate made of copper and connected to a high-voltage dc source. The electrode is a tungsten wire placed on a metal cylinder at about 30 mm from its axis [5].

Ozone can be produced from corona discharge process and oxygen irradiated by ultraviolet (UV) light [6]. The concentration of ozone according to the indoor air quality standards is 0.1 ppm [4]. Increasing the production of ozone in ESP air purifiers can cause serious health problems. Exposure levels as low as 100 ppb can reduce short-term lung capacity, and long-term exposure can cause lung disease and cancer. Table I shows the air quality that has been determined in the Air Pollution Index (API) table to discover the condition of ambient air quality to the public, which has been specified in the decree from the Indonesian Environmental Impact Management Agency (Bapedal) No. KEP-107/Kabapedal/II/1997.

TABLE I.
LIMIT OF AIR POLLUTION INDEX SI UNITS

Index	Category	*PM_{10} (μg/m^3)*	*Ozone (ppb)*
0 – 50	Good	50	120
51 – 100	Moderate	150	235
101 – 199	Unhealthy	350	400
200 – 299	Very Unhealthy	420	800
>300	Hazardous	500	1000
		600	12000

This study uses electrostatic filters with plate-type corona discharge to reduce particulate concentration in the air by using the fuzzy logic controller to prevent the increasing of ozone concentration due to excessive use of the electrostatic filters. In a previous experiment using ozone generators of Dielectric Barrier Discharge Plasma (DBDP) with spiral cylinder configuration, the concentration of ozone increases with the increasing of the voltage and the number of windings [5]. Therefore, in this study, the ozone generator is equipped with a fuzzy logic control algorithm to prevent the increasing of the ozone concentration during the air cleaning process. Fuzzy logic is one of the controlling methods that approach the human mindset in running a flexible system.

II. MATERIAL AND METHOD

Fig.1 illustrates an electrostatic filter system for experiments conducted in a sealed box of 60 cm x 40 cm x 40 cm in order to determine the optimal performance of electrostatic filters without being influenced by external factors, such as winds in the environment. The first experiment is the measurement of the sensor responses to the particulate concentrations during the air purification process. The second experiment is to measure the responses of electrostatic filters based on the number of ozone generators. The third experiment is to measure the performance of electrostatic filter using fuzzy logic-based control.

A. Air Quality Sensor

Air Quality Sensor (AQS) consists of a laser dust sensor (PMS3003), and an ozone gas sensor (MQ-131) used to measure air quality. The laser dust sensor PMS3003 is used to measure the concentration of PM2.5 and PM10 particulates in the air. The PMS3003 sensor uses the principle of laser light scattering to measure particulate concentrations of 0.3-10 μm in diameter.

Semiconductor gas sensors are often used for air or odor quality monitoring [7]. In this study, the measurement of ozone concentration level is conducted by semiconductor gas sensor MQ-131 which can detect ozone gas (O3) in the range of 10-1000 ppb. If the ozone gas is detected, the sensor resistance is lower along with the increasing of the gas concentration. In this experiment, the sample materials are smoke of cigarettes, paper, leaves, and plastics.

B. Electrostatic Filter

One method used to reduce particulates is to utilize the static electrical properties of the particulates attached by the charges, shown in Fig.2.

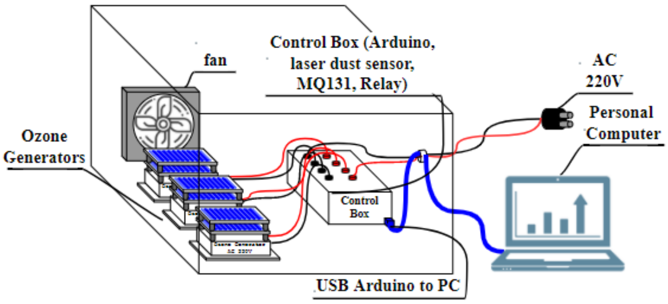


Fig.1 Design of electrostatic air filtration

When passing through between the two electrodes connected to a high voltage dc, it allows an electric field (EF) to ionize the particulate [6]. Eq. (1), (2), (3) shows the ionization process of oxygen gas so that the ozone molecule is formed because of electrical discharge by the two electrodes [8], [9], [10].

$$O_2 + e^- \rightarrow O^- + O_2 \quad (1)$$

$$O^- + O_2 \rightarrow O_3 + e^- \quad (2)$$

$$O_2 + O^- + M \rightarrow O_3 + M \quad (3)$$

Oxygen is oxidized by colliding with an electron (e -) which is produced by electrostatic filters. Furthermore, oxygen reacts with atoms O and M in the particulate form [8].

The reaction rate depends on the intensity of the electron flux through the gas. To capture particulates, it should pass through a strong electrostatic field where the particulate obtains an electrical charge. Then the charged particulate is attracted into the plate, which has the opposite electrical charge. The phenomenon is called electro-mechanic of particles. The particle electromechanical is forces and or torques exerted on small particles (and a group of particles) less than approximately 10-3 meters in diameter through the action of an electric or magnetic field, and the mechanics and dynamics induced by these forces. The electric or magnetic field may be imposed by external means (via electrodes or magnetic poles) or by other nearby charged, polarized, or magnetized particles and particle ensembles [11]. Eq.4 is used to consider the force on the particles passing through ESP based on Newton's law caused by EF in Eq.5 [12].

$$\sum F = m \times \frac{\partial u}{\partial t} \quad (4)$$

$$E_0 = 3.1 \times 10^4 \times \partial \left(1 + \frac{3.08}{\sqrt{\partial \times r}} \right) \quad (5)$$

where m is the particulate mass (kg), ∂u/∂t is the particle velocity (m/s), ΣF is the total force on particles, r is the distance between the electrodes with δ = 1 [5], [12].

Most of the dust particles have different shapes. For example, as illustrated in Fig.2, the ellipsoidal particulate enters an electric field so that it is ionized between two plates, which have the opposite electrical charges. On the first plate, they have more voltage (E1) so that the attraction appears between the particulates F1 and F2.

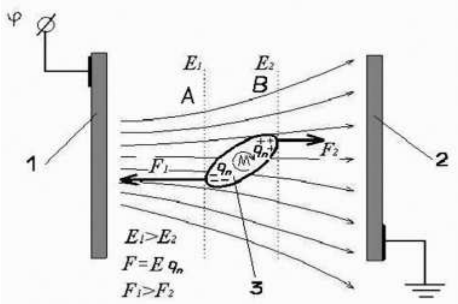


Fig.2 Polarization of particles

Since the electric field at point A is higher than the electric field at point B (E1 > E2), and force F1 > F2, it causes the particulate to have positive ions so that the positively-charged particulate (M) moves on a plate which has a larger electric field or connected to the ground [12]. The particles accumulated on the plate will not lose the charge as long as it is attached to the electrode. Thus, the ions produced by ESP will remove the particles from the airflow.

The electrostatic filter used in the experiment is ATWFS Portable Ceramic Ozone Generator powered by 220 V ac voltage input which can generate a high dc voltage of 3.1 - 3.5 kV. The Ozone Generator uses electrode-type corona discharge. The efficiency of the electrostatic filter is defined as the ratio of the final particulate concentration (Cf) to the initial value (Ci), as expressed in Eq.6.

$$Efficiency\ \ (\%) = \left| \frac{C_i - C_f}{C_i} \right| \times 100\ \% \quad (6)$$

C. Fuzzy Logic

One of the most important things in fuzzy logic is membership function (MF) which can translate into the output data accurately [13]. The set point used to form MF input based on the API shown in Table I. The fuzzy logic process consists of fuzzification, inference, and defuzzification [14]. Fuzzy logic control has two types of parameters taken from AQS that are error and Δerror. The error is obtained from the difference between the reference of 30μg/m3 and the PMS3003 sensor defined by Eq.7. The Δerror is obtained from the difference between the previous error and the error at t = 5 seconds defined by Eq.8.

$$error = reference - PM_{10} \quad (7)$$

$$\Delta error = error_{t=0} - error_{t=5\sec} \quad (8)$$

$$\mu[x] = \begin{cases} 0, x < a \\ \dfrac{x-a}{c}, a \le x \le c \\ \dfrac{b-x}{c}, c < x \le b \end{cases} \quad (9)$$

Fuzzification process is to convert crisp input to fuzzy input [14]. The input parameters are expressed in fuzzy sets representing each parameter in a fuzzy variable. In this study, the triangular type of MF is used in the fuzzification-defuzzification process. Fig.3 (a) - (b) is the fuzzy set which is formed in a triangle curve with MF indicating the mapping of parameter points into the membership value or μ[x]. Eq.9 is used to find μ[x] where c is the value of the midpoint of the curve, x is the sensor value, “a” is the upper limit of the curve, and “b” is the lower limit of the curve.

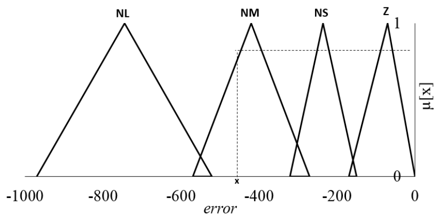
Table II shows the inference system consisting of a fuzzy rule to correlate between input and output data [13], [14]. The inference system using the method in Eq.11 is a min rule implication which uses the base operational operator of Zadeh “and” to obtain the value of μ(zj) by taking the smallest membership value between the elements in the corresponding set.

$$If\ X_i\ is\ A_1\ and\ ...\ moreover,\ X_n\ is\ A_n\ then\ Y\ is\ B \quad (10)$$

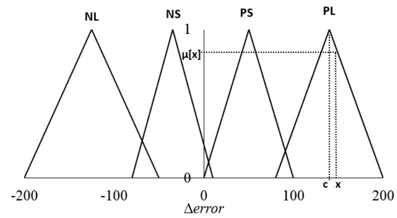
$$\mu_{(error \cap \Delta error)} = \min\ (\mu_{error}\ [x];\ \mu_{\Delta error}\ [x]) \quad (11)$$

TABLE II
RULE BASE OF FUZZY LOGIC CONTROL

error / *Δerror*	**Z**	***NS***	***NM***	***NL***
NL	S	M	L	L
NS	N	M	M	L
PS	N	S	M	L
PL	N	S	M	L

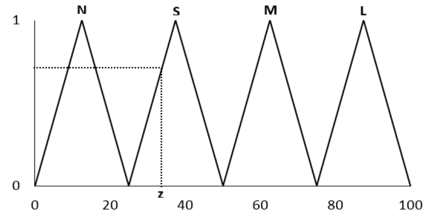


NL = Negative Large, NM = Negative Medium, NS = Negative Small, Z = Zero
(a)



NL = Negative Large, NS = Negative Small, PS = Positive Small, PL = Positive Large
(b)

Fig.3 The input membership function of fuzzy logic (a) *error* and (b) *Δerror*



N = Null (Off), S = Small (1 ozone generator), M = Medium (2 ozone generators), L = Large (3 ozone generators)

Fig.4 The output membership function of fuzzy logic

Defuzzification process is a fuzzy output conversion process into the crisp value [13], [14]. Eq.12 uses the center of area (COA) method, which can be obtained by taking the center point from the crisp output in Fig.4, where z is fuzzy output value that determines the number of ozone generators that will be activated, μ (zj) is MF the number of ozone generators. The solution is a value representing an output area, which states a decision in the form of constant value. Decision-making is based on the constant output value (z) from the established rule base of the two parameters.

$$z = \frac{\sum_{j=1}^{n} z_j \cdot \mu(z_j)}{\sum_{j=1}^{n} \mu(z_j)} \tag{12}$$

III. Result And Discussion

The experiments are performed on the system shown in Fig.5. The first experiment is a sensor test for the changes in particulate concentration carried out for 30 sec during the air condition in the room before and after the air purification process. The samples are introduced into the chamber after 5 seconds. Fig.6 shows that air pollutants rather than PM2.5 mostly produces the PM10. Fig.7 shows that ozone concentrations tend to be stable indicating the sample materials do not produce the ozone gas.

The second experiment is the electrostatic filter by using the number of ozone generators with the particulate concentration of ± 1000μg/m3. Fig. 8(a) shows that when an ozone generator is activated as an electrostatic filter, it can reduce 54.59% of PM10 with an initial concentration of 1002μg/m3 to 455μg/m3, and 44.46% PM2.5 with an initial concentration of 758μg/m3 to 421μg/m3 within 10 minutes. Fig. 8(b) shows that when two ozone generators are activated as electrostatic filters, they can reduce 68.02% of PM10 with an initial concentration of 1032μg/m3 to 330μg/m3, and 58.10% with an initial concentration of 759μg/m3 to 318μg/m3 within 10 minutes. Fig. 8(c) shows that when three ozone generators are activated as electrostatic filters, it can reduce 75.4128% of PM10 with an initial concentration of 1090μg/m3 to 268μg/m3, and 65.4354 % of PM2.5 with a concentration of 758μg/m3 to 262μg/m3 within 10 minutes. Fig. 8(d) is the ratio of ozone gas (O3) changes to the number of ozone generators during the air purification process.

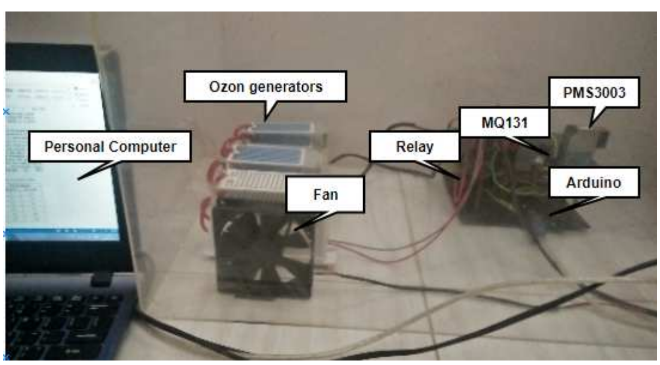


Fig.5 The electrostatic filtration system used in the experiments

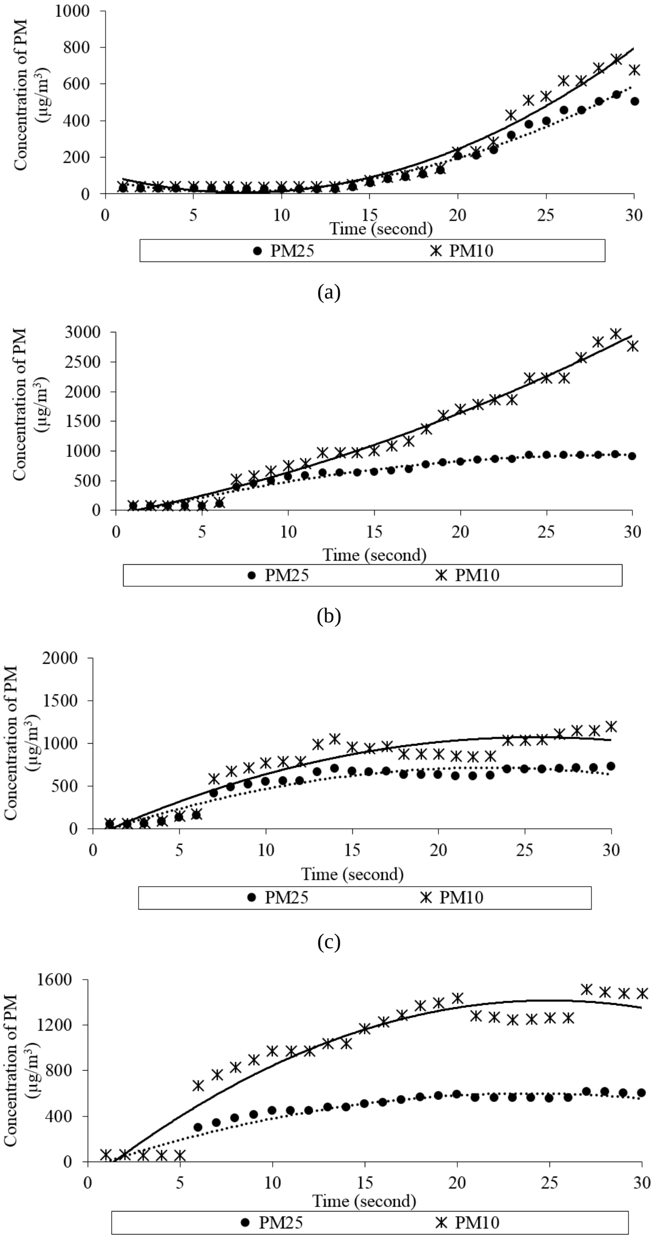


Fig.6 Responses of the laser dust sensor to combustions of (a) cigarette, (b) paper, (c) leaf, (d) plastic.

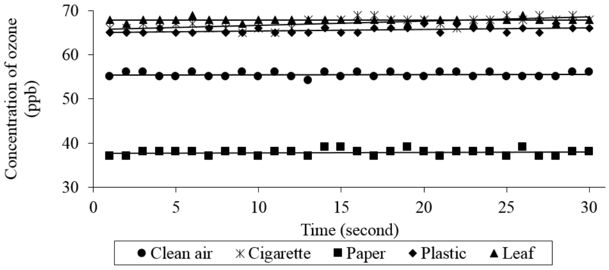
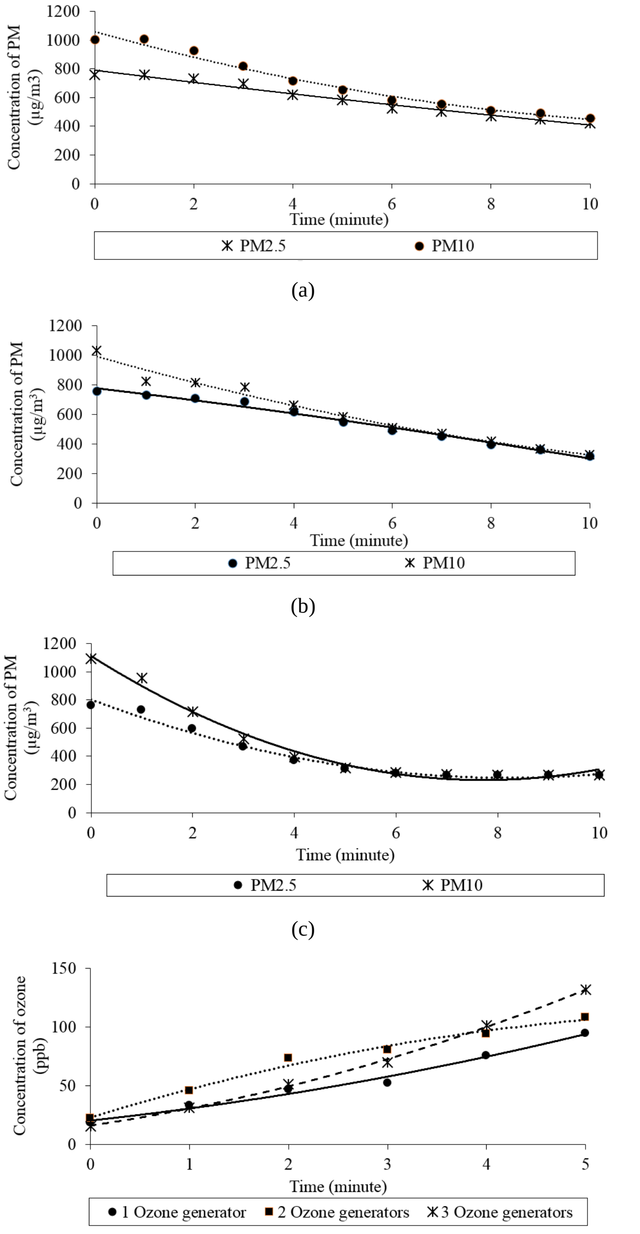


Fig.7 Responses of the ozone sensor to the air pollutions.

It shows that the use of electrostatic filters, which do not correspond to particulate levels in the air, will increase the ozone gas in the air as other air pollutants. Particulate values below 300μg/m3 can potentially increase the ozone gas during air purification process.

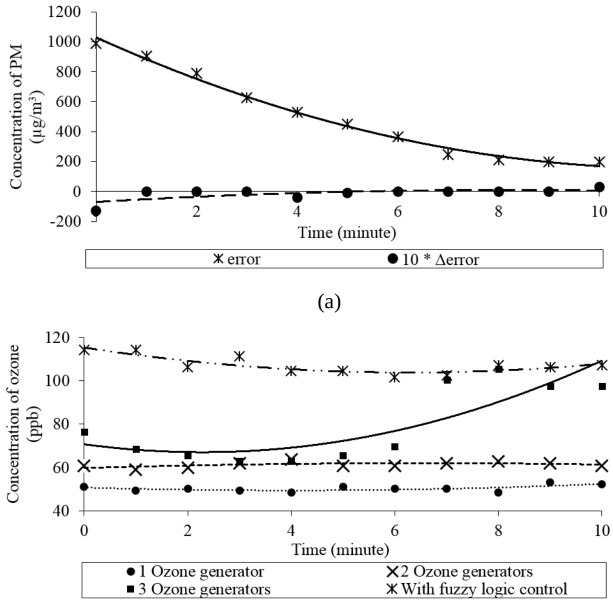


(d)

Fig.8. Responses of the sensors during the air purification processes without fuzzy logic control: (a) one ozone generator, (b) two ozone generators, (c) three ozone generators, and (d) clean air condition.

TABLE III
THE EFFICIENCY OF ELECTROSTATIC FILTER

Parameters	Efficiency to reduce PM_{10} (%)
One Ozon generator (without fuzzy logic control)	54.59%
Two Ozon generators (without fuzzy logic control)	68.02 %
Three Ozon Generators (without fuzzy logic control)	74.41%
Ozone Generators with Fuzzy Logic Control	80.10%



(b)

Fig.9 The experimental results of the electrostatic filter using fuzzy logic control: (a) particulate concentration, (b) ozone concentration

The third experiment is performed by an implementation of fuzzy logic control on the electrostatic filter using three ozone generators with a particulate concentration of about 1000μg/m3. Figure 9(a) shows the experimental results on a fuzzy logic-based electrostatic filter resulting in an efficiency of 80.10%, which reduces PM10 particles from an initial concentration of 990μg/m3 to 197μg/m3 within 10 minutes. Figure 9(b) shows that a fuzzy logic-based controlled electrostatic filter using three ozone generators produces a low level of ozone during the air purification process. Table III shows that a fuzzy logic-based electrostatic filter has a higher efficiency than that of without control.

IV. CONCLUSIONS

In this study, we have developed an electrostatic precipitation-based filter to remove particulates in the air. The electrostatic filter is an ozone generator comprising a plate-type corona discharge and a high voltage dc generator of about 3 kV. The experimental results show that the use of one, two and three ozone generators could reduce particulate matter of PM10 within 10 minutes by 55%, 68%, and 75%, respectively. However, the use of three ozone generators might increase the concentration of ozone gas in the air if the particulates in the air are below 300μg/m3. This can be harmful to human health. Therefore, this study has developed an electrostatic precipitation based air pollution control using fuzzy logic. Ozone sensor and laser dust sensor are employed as the parameters to determine the amount of charge released by ozone generators. This control system could reduce the particulates of PM10 by 80% within 10 minutes while maintaining a low level of ozone during the air purification process.

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