Int. J. Plasma Environ. Sci. Technol. 19(2) e02010 (11pp) 2025

International Journal of Plasma Environmental Science and Technology

Regular Paper (***Special Issue*** **of ICESP2024**)

DOI: 10.34343/ijpest.2025.19.e02010

Investigation of particle collection efficiency and ozone generation in AC and DC single-magnetic fluid filter toward a high performance air purifier with selective ozone generation

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Received: 30 December 2024
Revised: 1 March 2025
Accepted: 19 March 2025
Published online: 28 March 2025

Abstract

Air pollution, primarily caused by aerosols containing particulate matter (PM), is a significant global concern. To mitigate this issue, high-efficiency particulate air (HEPA) filters and electrostatic precipitators are commonly used due to their high collection efficiency. Aerosols encompass substances such as yellow dust, pollen, and PMs generated during fuel combustion. However, carbon-based combustion PMs, which possess high electrical conductivity, are difficult to collect using electrostatic precipitators due to re-entrainment. This challenge underscores the need for a high-performance air-purifying device capable of efficiently collecting various fine PMs while maintaining low pressure loss and a high collection rate. To address this, a single magnetic fluid (MF) filter has been developed. The MF filter employs magnetic fluid as the collecting electrode and utilizes electrostatic forces, Brownian diffusion, inertial forces, and gravity to collect PMs. Its design prevents the re-entrainment of carbon-based PMs due to the surface tension properties of the MF. This paper details the collection principle of the MF filter, the evaluation method for determining the PM collection rate using high-voltage DC and AC power and experimentally clarifies the PM collection mechanism and performance of the MF filter.

Keywords: Magnetic fluid, electrostatic precipitator (ESP), liquid electrode, air purification.

1. Introduction

According to the WHO, air pollution caused 6.7 million deaths globally in 2019 [1], making it a critical worldwide concern. Particulate matter (PM) is the primary contributor to air pollution, originating from a variety of sources, including human activities. PM is classified based on particle size, with particles smaller than 10 μm designated as PM_{10} and those smaller than 2.5 μm as $PM_{2.5}$ Exposure to PM poses significant health risks, including respiratory diseases and other adverse health effects [2–4]. The WHO has established an annual average exposure limit of 35 μg m^{-3}, yet most countries exceed this threshold [1].

The major sources of $PM_{2.5}$ are anthropogenic activities such as industrial processes, transportation, and fuel combustion [5]. PM generated by combustion primarily consists of carbon, which has high electrical conductivity. In PM collection, the use of electrostatic forces is an effective method for collecting particles of various sizes. Electrostatic precipitators (ESP) use this electrostatic force [6–8]. ESPs are characterized by low pressure loss and high collection efficiency. ESPs are widely used, and studies are also being conducted on them for purposes such as purifying air in tunnels [9] and inside aircraft [10], and purifying diesel exhaust gases [11].

However, because of the characteristics of PMs by charging, it is difficult to use carbon-based PMs. Because these PMs have high electrical conductivity, re-entrainment occurs [12, 13], and once collected, PMs are released into the atmosphere. The cause of this re-entrainment has been studied and methods to mitigate it have been proposed, wet ESPs have proven particularly effective in preventing re-entrainment [14].

HEPA filters are also widely used for particulate collection due to their high collection efficiency and lack of re-entrainment. However, these filters typically exhibit high pressure losses, such as 245 Pa, which is problematic. To address these issues, a novel filter employing water-based magnetic fluid (MF) as a collection electrode has been developed [15]. Studies have examined the relationship between the number of MF lumps and collection efficiency [16], as well as discharge phenomena from MF [17]. This filter combines MF and non-thermal plasma (NTP) technology.

MF is a colloidal solution containing fine ferromagnetic particles (approximately 10 nm in size) stabilized with a surfactant in a solvent. These particles respond to magnetic fields, enabling the MF to be fixed within a filter using a magnet. NTP enhances chemical reactions, and when plasma is generated in the atmosphere, oxygen is converted into ozone. Ozone, produced using high-voltage AC, exhibits strong oxidizing properties that enable it to function as a bactericide [18], deodorizer [19], and allergen inactivator [20]. However, excessive ozone concentrations can harm human health, necessitating a concentration limit of 0.1 ppm indoors. Therefore, a versatile air purifier capable of collecting PM with or without ozone generation is required.
To develop such an air purifier, this study investigates the selective generation of ozone using AC and DC power sources under varying applied voltages. This system can be used for a high-performance air purifier that can serve as a HEPA filter while selectively generating ozone. The previous study has explored the relationship between the number of MF lumps and collection efficiency under AC conditions but found that the efficiency for particles 0.3 μm or larger did not reach 99%. Moreover, the influence of voltage on PM collection efficiency remains unclear, and no experiments have been conducted under DC conditions.

This study aims to clarify the fundamental characteristics of PM collection and ozone generation using a single MF lump under both AC and DC conditions, targeting a PM collection efficiency of 99%. Experiments are conducted using a single MF filter equipped with a single MF lump. Under AC conditions, high voltage induces insulation breakdown in the air around the electrode, generating NTP. The MF filter, a dielectric barrier discharge (DBD) type, improves PM collection efficiency by charging particles. The relationship between applied voltage, PM collection efficiency, and ozone generation is systematically examined.

Under DC conditions, the study investigated PM collection efficiency and ozone generation through electrostatic forces. It is hypothesized that PM is charged by friction with air, enabling collection without NTP. This method creates an electric field without generating current, allowing for low-power operation. By elucidating the relationship between applied voltage, PM collection efficiency, and ozone generation under AC and DC conditions, this study demonstrates the potential for developing filters that can selectively generate ozone by switching between the two power sources.

2. Experimental

2.1 Principle of PM collection using electrostatic force

In general, five physical phenomena—gravitational force, centrifugal force, inertial force, Brownian diffusion, and electrostatic force—are utilized for PM collection. Among these, electrostatic collection is particularly effective for collecting PM across a wide range of particle sizes, leading to the development of various ESPs. One notable example is the two-stage ESP, a Penney-type ESP that employs a DC corona discharge [21]. The Penney-type ESP consists of two distinct sections: a charging section and a collecting section.

For PM collection, assuming that the PMs are spherical, and that the Reynolds number is low, the particle migration velocity v_e due to the electrostatic force can be expressed using Eq. (1).

$$v_e = C_c \frac{qE}{3\pi\mu d_p} \tag{1}$$

where q is the charge, E the strength of the applied electric field, μ the fluid viscosity, d_p the PM diameter, and C_C the Cunningham correction factor. C_C is given by

$$C_c = 1 + Kn\left(\alpha + \beta^{-\frac{\gamma}{Kn}}\right) \tag{2}$$

where Kn is the Knudsen number, and it is given by

$$Kn = \frac{2\lambda}{d_\mathrm{p}} \tag{3}$$

where λ is the mean free path of fluid molecules. In the case of air, $\lambda = 6.65 \times 10^{-8}$ m and α, β, and γ are the theoretical or empirical correction parameters. In this study, based on previous studies, $\alpha = 1.257$, $\beta = 0.400$, and $\gamma = 1.100$ for $d_\mathrm{p} \geq 1$ μm, as reported by Davies [22], and $\alpha = 1.165$, $\beta = 0.483$, and $\gamma = 0.997$ for $d_\mathrm{p} < 1$ μm as reported by Kim [23] are used.

For electrostatic collection, the PM must be charged via two mechanisms: field and diffusion charges. In the field-charging case, the charge q_field is given by the Pauthenier equation;

$$q_\mathrm{field}(t) = \frac{q_\mathrm{s} e B_\mathrm{ion} N_\mathrm{ion} t}{e B_\mathrm{ion} N_\mathrm{ion} t + 4\varepsilon_0}, \quad B_\mathrm{ion} = \frac{v_\mathrm{e}}{E} \tag{4}$$

where q_s is the saturation charge, e is the elementary charge (1.60×10^{-19} C), B_ion is the ion mobility, N_ion is the ion concentration, and ε_0 is the permittivity of a vacuum (8.85×10^{-12} F m^{-1}). The saturated charge q_s for a dielectric is given by

$$q_\mathrm{s} = 4\pi\varepsilon_0 \left(\frac{3\varepsilon_\mathrm{p}}{\varepsilon_\mathrm{p}+2}\right) E r_\mathrm{p}^2 = \pi\varepsilon_0 \left(\frac{3\varepsilon_\mathrm{p}}{\varepsilon_\mathrm{p}+2}\right) E d_\mathrm{p}^2 \tag{5}$$

where ε_p is the relative permittivity of the PM and r_p is the radius of the PM. It is noted that $\varepsilon_\mathrm{p} = \infty$ for a conductor. In the PM collection using electrostatic forces, the saturation charge is achieved shortly after the PM enters the device. Therefore, q_field can be considered as q_s. In this case, the charge q_field is given by Pauthenier's saturated charge [24]:

$$q_\mathrm{field} = \left(\frac{3\varepsilon_\mathrm{p}}{\varepsilon_\mathrm{p}+2}\right) \pi\varepsilon_0 E d_\mathrm{p}^2 \xrightarrow{\varepsilon_\mathrm{p}=\infty} 3\pi\varepsilon_0 E d_\mathrm{p}^2 \quad \text{for an ideal conductive PM} \tag{6}$$

In the diffusion charging case, q_diff is given by White [25]

$$q_\mathrm{diff} = \frac{2\pi\varepsilon_0 k_\mathrm{B} T d_\mathrm{p}}{e} \ln\left(1 + \frac{N_\mathrm{ion} e^2 v_{ion} d_\mathrm{p} t}{8\varepsilon_0 k_\mathrm{B} T}\right) \tag{7}$$

where k_B is the Boltzmann constant (1.38×10^{-23} J K^{-1}), and v_ion is the mean thermal velocity of the ions [26].

These two charging mechanisms are highly effective for charging particles of a wide range of sizes, and by substituting Eqs. (6) and (7) into Eq. (1), the migration velocity of the particles owing to electrostatic forces is calculated.

2.2 Principle of PM collection using single-MF filter

An MF is a functional fluid that reacts with a magnetic field. First, the structure of the MF is explained. When water is used as the medium, a double surfactant coating is applied so that the hydrophilic parts come into contact with water. Thus, the MFs are stable in the dispersion medium. A characteristic phenomenon of MFs is the spike phenomenon. This phenomenon occurs when the surface of the MF changes and the critical magnetic flux density of the MF exceeds [27]. For the water-based MF used in this study (W-40, Ichinen Chemicals Co., Ltd.,), the theoretical critical magnetic flux density is $B_\mathrm{c} = 86.6 \times 10^{-4}$ T [28]. The conductivity of the MF is 6.59 mS cm^{-1}, which is measured using a conductivity meter (IWC-6SD, CUSTOM Corporation).

The PM collection principle of a single MF filter is illustrated in Fig. 1. Pollutant gases, including PMs, flowed into the filter. The MF lump is fixed in a flow channel using three neodymium magnets. The magnetic field generated by the magnets is only used to hold the MF and generate spikes.

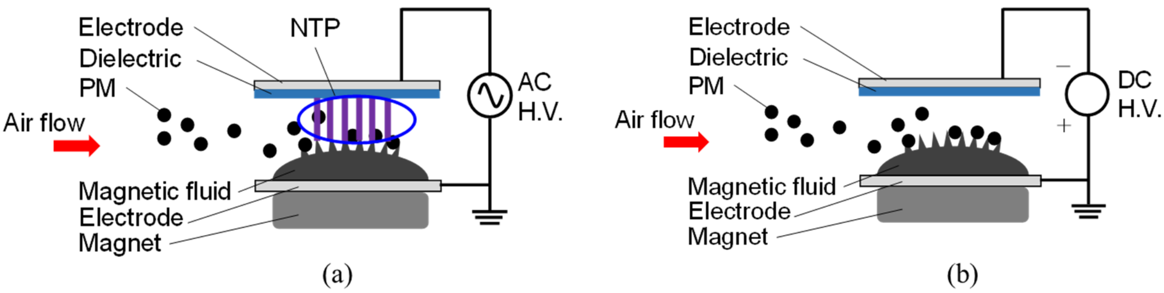

Fig. 1. PM collection principle of single-MF filter. (a) AC case, and (b) DC case.

Fig. 1 (a) shows the principle of the AC case, which is generated from the MF by applying a high voltage to the electrodes; thus, the PM becomes charged and is probably collected on the surface of MF by an electrostatic force. NTP is generated in the case of high-voltage AC. Therefore, ozone is generated. The ferromagnetic particles are covered by water with the aid of surfactants. This water could play the role of a barrier to prevent ozone-induced oxidation of ferromagnetic particles and surfactants. In other words, MF is hardly oxidized by ozone. Although the electric field may be deformed by the presence of MF to penetrate perpendicularly to the MF surface, it is effective for PM collection. In the NTP case, MF has little function as a dielectric barrier because it contains a large amount of water that has a relatively high relative permittivity of 80. Ozone generated by the discharge can remove a certain amount of PM by oxidation [29]. When the collection capacity is lost due to PM accumulated on the MF surface, the MF should be replaced. It is possible that the mother liquid of MF could evaporate depending on the humidity for long-term use. This issue could be solved by placing MFs on both the top and bottom surfaces within the MF filter. Because the primary objective of this study is to clarify the fundamental characteristics of the MF filter, the MF is placed only on the bottom surface. However, the collection characteristics when the MF is placed on both the top and bottom surfaces will be investigated in the future study.

Fig. 1 (b) shows the principle of the DC case: NTP is not generated; therefore, only an electric field is generated, which is thought to enable collection with less energy. In this case, the PM is charged owing to friction with the air.

In both cases, the principles of PM collection include gravity, inertial forces, Brownian diffusion, and electrostatic forces. Gravitational and inertial forces are effective collection methods for large PMs. Furthermore, Brownian diffusion is effective for PMs with small diameters. Electrostatic force is an effective collection method for fine PMs with a wide range of diameters, owing to the effects of diffused and collision charges. Fig. 1 illustrates the collection principle of the MF filter. As the MF is a collection electrode, the collected PMs is held by the surface tension of the MF. Therefore, re-entrainment, which is a major problem in electrostatic force collection, can be prevented. In other words, the MF filter can collect PM via electrostatic forces without re-entrainment. This is one advantage of the proposed method.

2.3 Experimental method and setup

The study investigates the PM collection efficiency and ozone generation associated with AC and DC power sources. It aims to clarify the fundamental characteristics of a single MF filter, utilizing a lump of MF, to enhance its PM collection efficiency. The structure of the single-MF filter is illustrated in Fig. 2. The filter has a simple configuration comprising a glass plate, acrylic plate, neodymium magnets, stainless steel pipe, aluminum tape, and MF. For this filter, 3.60 g of MF is installed as a lump. The MF is secured using three neodymium magnets, with a surface magnetic flux density of 490 mT, which fully satisfies the critical magnetization threshold. Fig. 3 presents images of the MF in filter. Figs. 3 (a) and 3 (c) show the case where a magnetic field is applied, and Figs. 3 (b) and 3 (d) show the case where no magnetic field is applied. This magnetization induces surface instability in the MF, resulting in spikes as shown in Fig. 3 (a). The MF made contact with the aluminum tape, serving as a grounding electrode.

The single-MF filter operates as a dielectric barrier discharge type, where the dielectric is in contact with the high-voltage electrode. Consequently, when DC power is applied, discharge does not occur, unlike in corona discharge. For the AC case, the input voltage is adjusted using an AC variable transformer (MVS520, Yamabishi Denki) and supplied to an AC high-voltage power supply (LHV-13AC, Logy Electric Co., Ltd.). For the DC case, a highly negative voltage is applied to create an electric field using a DC power supply (M10-

HV10000A, MCP) capable of generating up to 10 kV. The system's total power consumption is measured using a watt checker (TAP-TST7, Sanwa Supply Co., Ltd.).

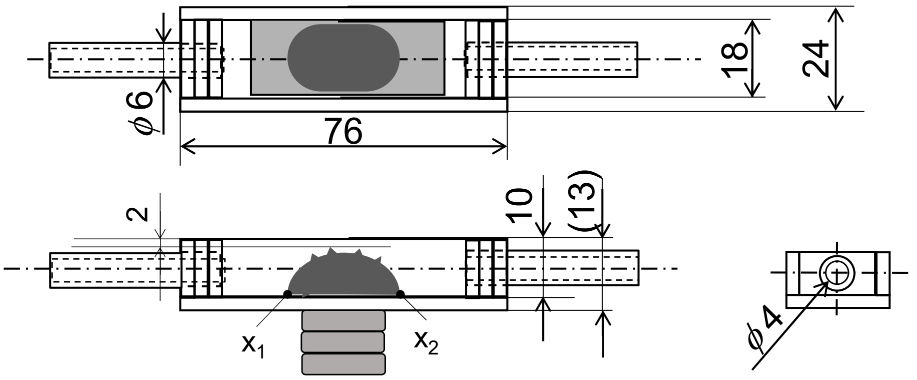

Fig. 2. Structure of single-MF filter.

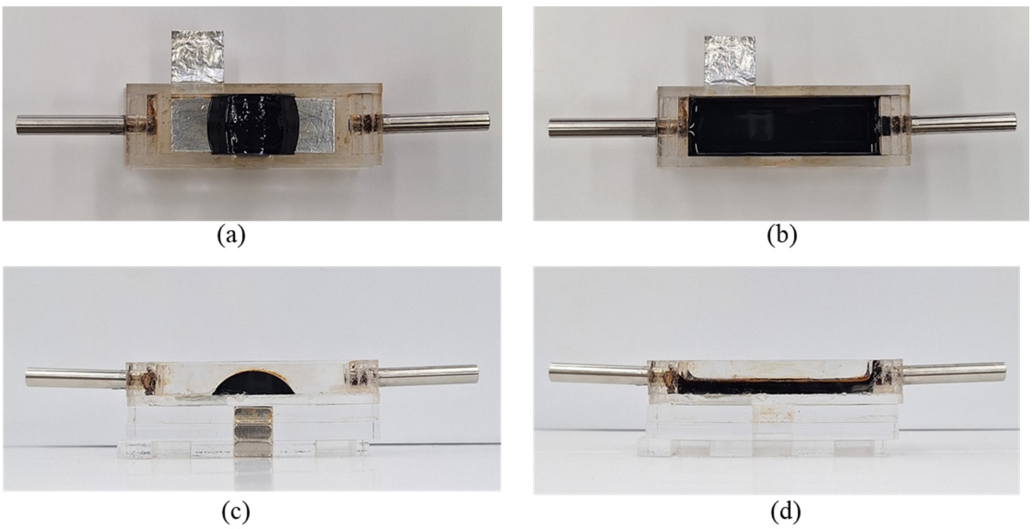

Fig. 3. MF image of (a) top view with magnetic field, (b) top view without magnetic field without magnetic field, (c) front view with magnetic field and (d) front view without magnetic field.

The experimental procedure consists of two steps to evaluate PM collection efficiency. The setup is depicted in Fig. 4. In the first step, two types of gases are prepared: clean air with minimal PM and diesel engine exhaust gas. Clean air is obtained by filtering ambient air through a membrane filter with a pore size of 0.20 µm and storing it in a 20 L sampling bag using a vacuum pump. Diesel exhaust gas is collected using a diesel engine generator (KDE2.0E-60 Hz, KIPOR). After a 5-minute warm-up operation with a 500 W engine load, a portion of the exhaust gas is sampled and stored in a 20 L sampling bag in the same manner as the clean air. The temperature of the process gas is 19.7 °C, and the atmospheric humidity is 30%. Fig. 4 provides a schematic representation of the experimental setup. Two sampling bags are used, as shown in Fig. 4. The exhaust gas is diluted with clean air because of the PM content in the exhaust gas is extremely high, and the number exceeds the measurement range of the particle counter. The number of PMs contained in the exhaust gas is measured using a particle counter (DT-9883M, Shenzhen Everbest Machinery Industry Co., Ltd.). In this study, the PM collection efficiency is measured using the number of outstanding PMs N_{exh}, number of PMs passing through the single-MF filter when applying DC high-voltage N_{DC} and number of PMs passing through the single-MF filter when applying AC high-voltage N_{AC}. The collection efficiency is calculated using Eqs. (8) and (9), respectively.

$$\eta_{\mathrm{DC}} = \frac{N_{\mathrm{exh}} - N_{\mathrm{DC}}}{N_{\mathrm{exh}}} \tag{8}$$

$$\eta_{AC} = \frac{N_{exh} - N_{AC}}{N_{exh}} \tag{9}$$

The exhaust gas flow channel could be altered using a valve installed in the flow path. The channel without the MF filter is utilized for measuring the exhaust particle count, N_{exh}, while the channel with the MF filter is used for measuring the particle counts under N_{AC} and N_{DC} conditions. Each measurement is repeated six times to determine the PM collection efficiency. The average of the six measurements is taken as the final collection efficiency, with the standard error used to evaluate variations. Each measurement takes 15 s, and 6 trials are measured each voltage step, so that it requires 90 s to measure.

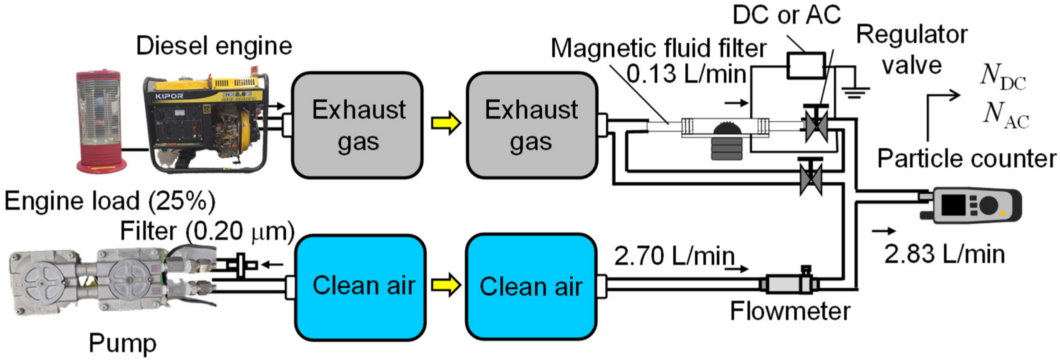

Fig. 4. Experimental setup of PM collection evaluation.

The method for measuring discharge current and voltage is detailed below. The waveforms are recorded by connecting a high-voltage probe (P6015A, Tektronix Inc.) and a current probe (P6021A, Tektronix Inc.) to an oscilloscope (SDS6062, Owon Technology Inc.). The discharge voltage is measured by directly contacting the high-voltage probe to the electrode on the glass plate side. The discharge current is measured by placing the current probe around a conductor connected to the MF.

For ozone concentration measurements, atmospheric air is pumped into the filter at a flow rate of 1.0 L min^{-1}. The ozone concentration generated by the NTP in the MF filter is measured using an ozone detection tube (No. 18M, Gastec Corporation). Five measurements are conducted, with the results evaluated based on averages and standard errors. The ozone concentration is specifically measured at the outlet of the filter. Nitrogen monoxide (NO) and nitrogen dioxide (NO_2), which interference with ozone detective tube, are also measured using a detective tube (No. 10, Gastec Corporation). Carbon monoxide (CO), which affects ozone production, is also measured using a detective tube (No. 1L, Gastec Corporation). Additionally, carbon dioxide (CO_2) is measured using a detective tube (No. 2LC, Gastec Corporation) to evaluate the amount of carbon monoxide produced. Moreover, lower hydrocarbons, which (HC) are relatively easily produced by NTP discharge, are therefore measured using a detective tube (No. 103, Gastec Corporation).

3. Results and discussion

3.1 Results and discussion of AC case

Fig. 5 shows the results for AC. Fig. 5 (a) shows the PM collection efficiency, (b) shows the power consumption, (c) shows the ozone concentration, and (d) shows the calculated migration velocity due to the electrostatic force. The results of PM collection efficiency are discussed. The number of PMs in diesel exhaust gas is 6.2×10^6 particles/L for particle size $d_p \geq 0.3$ μm, 3.8×10^6 particles/L for $d_p \geq 0.5$ μm, 1.3×10^6 particles/L for $d_p \geq 1.0$ μm, 1.0×10^5 particles/L for $d_p \geq 2.5$ μm, 1.3×10^4 particles/L for $d_p \geq 5.0$ μm, 3.7×10^3 particles/L for $d_p \geq 10.0$ μm. The PM collection results from the AC are fitted using a fourth-order equation. This is not a theoretically derived equation; however, it represents the PM collection characteristics of AC.

Fig. 5 (a) present the PM collection efficiency, and the collection efficiency in PM collection using AC decreases significantly around applied voltage 5 kV. Air has the characteristic of being easily positively charged [30]. Therefore, it can be inferred that the air becomes positively charged while the particles acquire a negative charge due to friction caused by the relative speed difference between the particles and the air. It can be considerd that at AC voltages below 5 kV, PM becomes negatively charged due to friction with the atmosphere and is collected through the action of electrostatic forces within the filter. At approximately 5 kV which is near the discharge voltage of 4.08 kV, positive ions are generated due to weak discharges. These ions neutralize the charged PM, nullifying the electrostatic force and making PM collection ineffective. Beyond 5 kV, PM is thought to be collected again as it becomes statically charged by the discharge process. In the low-voltage region where NTP discharge does not occur, it is considerd that PM is charged through atmospheric friction, and electrostatic forces facilitate its collection. In the high-voltage region, where NTP discharge is evident, PM is charged directly by the discharge and subsequently collected by electrostatic forces. However, power consumption begins to rise around 5 kV, indicating slight electron movement. The targeted particulates in this study are carbon-based diesel exhaust particulates, which have low electrical resistance. These particulates can neutralize the charge obtained through atmospheric friction, reducing the effectiveness of the electrostatic forces and consequently decreasing the collection rate. Nonetheless, based on the results, AC operation can collect particulates without generating ozone at voltages below 8 kV. For particles with $d_p \geq 0.3$ μm, a collection rate of 10% can be achieved at 8 kV or higher, reaching 15% for higher voltage conditions. Even when a applied voltage is 10 kV, no deformation of the MF is visually observed, nor is there any change in the air gap.By adjusting the AC voltage, it is possible to balance ozone generation and PM collection. To achieve a PM collection efficiency of 99%, ten lumps of MF would be necessary. The maximum power consumption of the system in AC operation is 56 W, and it has been observed that power consumption increases quadratically with voltage.

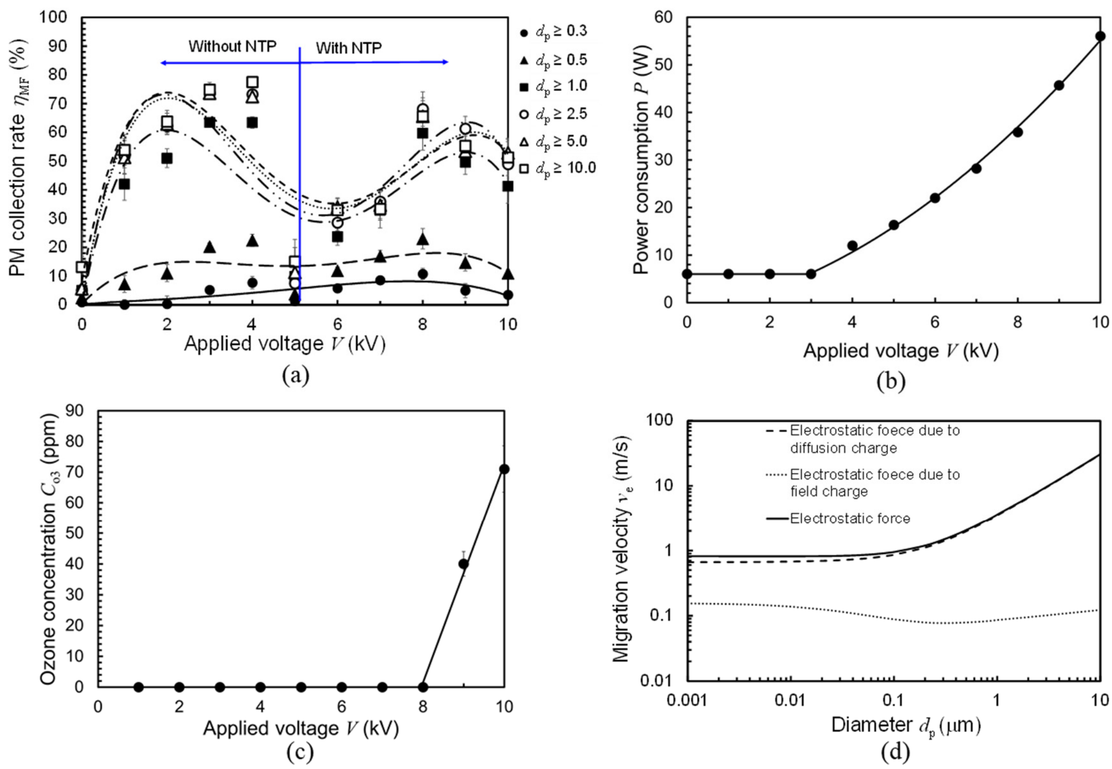

Fig. 5. Results of AC case, (a) PM collection efficiency, (b) power consumption, (c) ozone concentration, and (d) calculated migration velocity due to electrostatic force at 5 kV.

The results of ozone concentration generated by the NTP are discussed next. Fig. 5 (c) shows the ozone concentration results for the AC operation using a single MF filter. The maximum ozone concentration reached 71 ppm (equivalent to 20 mg h^{-1}), indicating a proportional increase in ozone concentration with discharge voltage. In addition, NO, NO_2, HC and CO are not detected. CO_2 concentration is approximately 600 ppm.

Fig. 5 (d) illustrates the migration velocity at 5 kV. The migration velocity due to the field charge is calculated using Eq. (1), with the charge determined by Eq. (4). Similarly, the migration velocity due to the diffusion charge is calculated using Eq. (1), with the charge given by Eq. (5). Both migration velocities contribute to PM collection. From these results, it is evident that larger PM particles are more effectively collected due to the influence of diffusion charges. Conversely, smaller PM particles, particularly those with diameters of 0.1 μm or less, are more challenging to collect.

Comparing the MF before and after the experiment, no discoloration or aggregation due to surfactant degradation is visually observed, indicating that oxidation due to ozone does not occur.

3.2 Results and discussion of DC case

Fig. 6 shows the results for the DC case. Fig. 6 (a) shows the PM collection efficiency. Fig. 6 (b) shows the power consumption, and the results of PM collection efficiency are discussed. PM collection efficiency η is generally expressed by the Deutsch's formula, which incorporates flow rate Q, collection area A, and migration velocity v_e, as follows [14]:

$$\eta = 1 - \exp\left(-\frac{v_e A}{Q}\right) \tag{10}$$

Here, v_e is proportional to E as shown in Eq. (1). Considering that PM is charged by two effects, diffusion charge and collision charge, total charges q_{total} can be expressed as follows:

$$q_{total} = q_{field} + q_{diff} \cdot \tag{11}$$

Therefore, v_e can be expressed as follows:

$$v_e = C_c \frac{q_{total} E}{3\pi\mu d_p} = C_c \frac{(q_{field} + q_{diff}) E}{3\pi\mu d_p}, \quad E = \frac{V}{d} \tag{12}$$

Substituting this into Eq. (10),

$$\eta = 1 - \exp\left(-\frac{C_c (q_{field} + q_{diff}) VA}{3\pi\mu d_p Q d}\right) = 1 - \frac{1}{\exp\left(\frac{C_c q_{field} VA}{3\pi\mu d_p Q d}\right)\exp\left(\frac{C_c q_{diff} VA}{3\pi\mu d_p Q d}\right)} \tag{13}$$

However, because the air gap d over the MF is not constant, the electric field E is also not constant. Therefore, the mean air gap over the MF is introduced into Eq. (13) as follows:

$$\eta = 1 - \frac{1}{\exp\left(\frac{C_c q_{field} VA}{3\pi\mu d_p Q d_{mean}}\right)\exp\left(\frac{C_c q_{diff} VA}{3\pi\mu d_p Q d_{mean}}\right)}, \quad d_{mean} = \frac{1}{\Delta x}\int_{x_1}^{x_2} d dx \cdot \tag{14}$$

where $d_{mean} = 7.4$ in this experiment, Δx is the bottom length of the MF, and x is the flow direction. The number of PMs in diesel exhaust gas is 5.9×10^6 particles/L for particle size $d_p \geq 0.3$ μm, 3.5×10^6 particles/L for $d_p \geq 0.5$ μm, 1.3×10^6 particles/L for $d_p \geq 1.0$ μm, 1.1×10^5 particles/L for $d_p \geq 2.5$ μm, 1.2×10^4 particles/L for $d_p \geq 5.0$ μm, 3.7×10^3 particles/L for $d_p \geq 10.0$ μm. In Fig. 6 (a), the plots are experimental data, and the lines indicate theoretical η obtained by Eq. (14). It is evident that the PM collection efficiency improves as the voltage increases and at $d_p \geq 0.3$ μm, $\eta = 26\%$. PM collection efficiency of $d_p \geq 1.0$ μm is 90.5%, $d_p \geq 2.5$ μm is 99.3%, $d_p \geq 5.0$ μm is 99.9%, and $d_p \geq 10.0$ μm is 100% at $V \geq 9$ kV. As a trend, PM collection efficiency η of larger particles have a larger standard error. In addition, the efficiency η plotted of larger particles becomes higher than the theoretical value. Inertial and gravitational forces act effectively on larger particles. For larger particles, the collection is influenced not only by electrostatic forces but also by inertial forces and gravity. This is the possible reason why the collection efficiency for larger particles is higher than the theoretical one due to electrostatic forces. From Fig. 6 (b), it is evident that the power consumption increased proportionally with the applied voltage, reaching a maximum of 35 W. However, because the standby power is 28 W, the power consumed by the system is approximately 7 W. Because NTP is not generated in the case of DC, it is considered that most of the power is consumed by the power supply and load. In this study, NTP generation is not observed visually because a DC is used; therefore, ozone is not generated because the atmosphere does not undergo any chemical reactions. In addition, as in the AC case, power consumption rises sharply when NTP occurs. This rise is not confirmed in this experiment. In other words, the power measurements also confirmed that NTP is not generated.

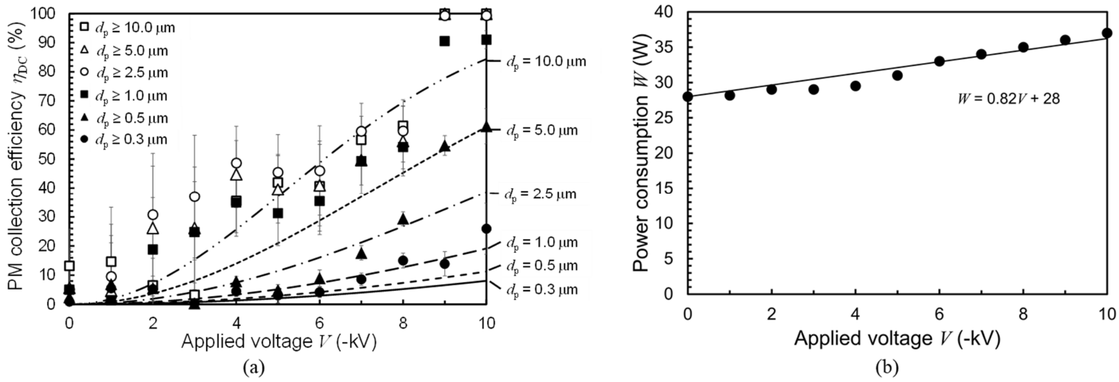

Fig. 6. Results of DC case, (a) PM collection efficiency, (b) power consumption.

Furthermore, in the case of DC, because NTP is not generated, it is believed that the PM becomes charged owing to friction with the atmosphere and is collected, similar to AC below 5 kV.

Comparing AC and DC, it is found that DC had a higher PM collection efficiency, and that AC is capable of selectively generating ozone.

4. Conclusion

The following conclusions are derived from the study on MF filters using AC and DC:

1. Experiments with a single MF filter revealed distinct collection principles depending on whether discharge occurs. For PMs with $d_p \geq 0.3$ μm, the collection rate is approximately 10% in the AC case, whereas it is approximately 25% in the DC case.
2. At approximately 5 kV, the collection efficiency decreases due to the cancellation of charges on PM and NTP, causing the electrostatic force to become ineffective. Without discharge, PM is charged through atmospheric friction and collected by electrostatic forces, while with discharge, PM is charged by NTP and similarly collected by electrostatic forces.
3. In DC operation, PM can be charged by friction with air and collected even without NTP occurrence. Theoretical calculations suggest that the collection efficiency can be enhanced by the charge generated from the electric field.
4. In DC mode, no discharge occurs, resulting in the absence of current flow. This allows PM collection with low energy consumption. The actual power consumption, excluding standby power, is approximately 7 W, with most of the energy attributed to power supply resistance.
5. A comparison of AC and DC indicates that high-voltage AC is suitable for PM collection accompanied by ozone generation, while high-voltage DC is more effective for PM collection without ozone generation.
6. It is determined that 10 lumps of MF are required to achieve the same collection efficiency as a HEPA filter.

This study clarified the principles of PM collection using single MF filters. With AC, the PM collection efficiency varies significantly around the dielectric breakdown voltage. Low voltages allow PM collection without ozone generation, while high voltages enable both ozone generation and PM collection. In DC mode, PM collection occurs due to electrostatic forces arising from diffusion and electric field charging, without ozone generation. These findings demonstrate that, by selecting between AC and DC and adjusting the applied voltage, it is possible to achieve selective ozone generation and PM collection.

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