Effect of electric potential across electrodes for trapping joss smoke particles in DBD plasma atmospheric pressure

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Abstract. Particulate matters (PM) in air pollution have been known to be the cause of respiratory diseases. Many researchers have investigated methods of trapping the particulate matter. In this work, the trapping of smoke particles generated from a joss stick by using a dielectric barrier discharge (DBD) system operated under the atmospheric pressure condition was investigated. DBD system consists of an inner electrode which is made of aluminum wire filaments that are placed inside the acrylic cylindrical tube, and the outer electrode is made of metallic wrap around the tube. The electrodes were connected to a 50 Hz high voltage AC source which was adjusted to 0 V, 5kV, 7kV, and 10kV. A ventilating fan was used for draining the smoke particle from the joss stick through the inner electrode with an airflow velocity of 2.68 m/s. The effect of electric field and plasma trapping the smoke particles was investigated. Results from the experiment were further compared with a study by simulation. It was found that the smoke particle density measured by applying an electric potential difference of 0 V and 5 kV was similar; both conditions showed the highest smoke density values. On the other hand, when the electric potential difference was adjusted to 7 kV and 10kV, it was found that the smoke particles density decreased by 90%. The experiment also illustrated when the electric potential difference was increased high enough such that plasma was produced at 7 kV and 10 kV, the smoke particle density released from the tube was similar. Nevertheless, when comparing the mass of particles collected from the inner electrode with the plasma condition, it was found that the mass collected increased more than the operating condition with an electric potential difference of 0 kV and 5 kV without plasma.

1. Introduction

One of many causes of respiratory diseases has come from particulate matter (PM) in air pollution [1], and it is a major concern in Bangkok and many other cities [1]. Combustion of fuel from vehicles can generate PM are the cause of health risk, therefore; investigation on means to reduce these particles has been gaining interest.

There are many ways to reduce the particles in the air one of which is trapping. The particles can be trapped by using nano-fiber filters [2-6] or using an electrical discharge system [7-9]. In this research, a type of electrical discharge system based on dielectric barrier discharge (DBD) is investigated. For example, removal of PM in a hen house [7] using a dry filter and electrostatic precipitator (ESP) trap were compared. It was found that the efficiency of the dry filter in trapping PM 10 was 40.1%, but its efficiency was not significant for trapping PM 2.5. In comparison, the trapping efficiency of ESP was 57% for PM 10 and it was 45.3% for PM 2.5. Huang *et al*. [8] also studied the trapping of PM 2.5 using the DBD system. They showed that 53% of PM 2.5 was trapped by the DBD system and both their experimental results and their simulation results were compared and are in good agreement. Jaworek *et al*. [9] studied the efficiency of a two-stage electrostatic plate to trap PM 2.5. The first plate was used to discharge the gas that is flowing through the plate. The second plate electric field was applied to collect the charged particles. The efficiency of PM 2.5 trapping using DC and AC power supply was compared. The results showed that the number of the particle collected by using AC was more than 90% and from DC was more than 95%.

From the reviews, an electrics discharge system can efficiently trap the particulate matter. In this investigation, we investigate also the effect of plasma from a DBD system that may be an additional cause of PM removal.

2. Simulation and experiment

The dielectric barrier discharge (DBD) system for the experiment consists of a transparent acrylic cylindrical tube shown in figure 1. The outer of the tube is covered by an outer metallic cylindrical electrode. The aluminum filament is used as an inner electrode and is placed inside the acrylic tube. The length of the acrylic cylindrical tube is 10 cm, the diameter of the cylindrical tube is 3 cm and both the outer and inner electrode is 6 cm long. A 50 Hz ac power supply is used in this work and is connected to the electrodes. The operation is at atmospheric pressure condition.

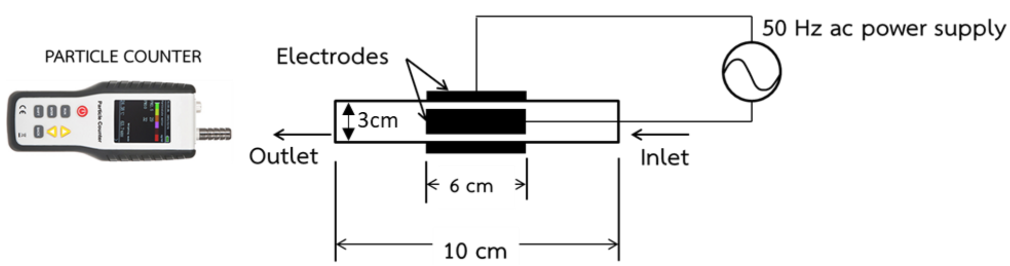


Figure 1. Diagram showing experiment setup of DBD system.

2.1. Simulation of plasma and smoke particle's motion

In this research, plasma characteristics and motion of smoke particles are simulated by using a simulation program (COMSOL) [10]. The dynamics of plasma can be explained by using both transport theory and electrostatics theory. A laminar flow model was conducted to replicate the airflow through the inner electrode placed inside the acrylic tube. Particulate matters were included in the airflow, and Newton's law of motion was used to estimate the movement of the particles.

The electric field between the electrodes was calculated by using an electrostatic theory that this electric field affects the particles in plasma. The equation is shown as follows;

$$\vec{\nabla}\cdot\left(\varepsilon\vec{E}\right)=\rho_f \tag{1}$$

where $\vec{E}$ is an electric field in medium (N/C), ρ_f is the density of free charge in the space (C/m^3), ε is the permittivity of the medium (C^2/N·m^2).

The characteristics of plasma such as the number density of electrons and the temperature of plasma were estimated by using transport theory. The transport equations of the electron can be shown as;

$$\frac{\partial n_e}{\partial t}+\vec{\nabla}.\vec{\Gamma}_e = R_e - \vec{u}\cdot\vec{\nabla}n_e \tag{2}$$

$$\frac{\partial n_\varepsilon}{\partial t}+\vec{\nabla}.\vec{\Gamma}_{en}+\vec{E}.\vec{\Gamma}_e = S_{en} - \vec{u}\cdot\vec{\nabla}n_\varepsilon + Q \tag{3}$$

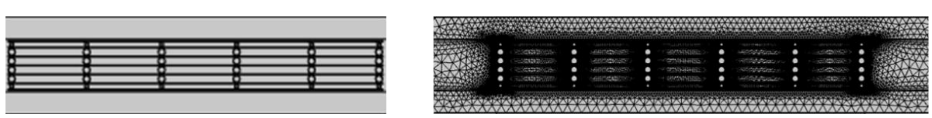
where n_e is the number density of electrons (m^{-3}), n_ε is electron energy density (J/m^3), R_e is an electron creation rate (m^{-3}·s^{-1}), S_{en} is an energy loss/gain from inelastic collision (W/m^3), $\vec{u}$ is a vector field velocity (m/s), Q is a total heat source (W/m^3), $\vec{\Gamma}_e$ is an electron flux (m^{-2}·s^{-1}), and $\vec{\Gamma}_{en}$ is an electron energy flux (W/m^2).

A laminar flow model was used to calculate dynamics parameters of the particles such as the velocity of particles, and pressure. The equation that was used to represent the model is shown as follow;

$$\rho\left(\vec{u}\cdot\vec{\nabla}\right)\vec{u} = \vec{\nabla}\cdot(p\boldsymbol{I}+\boldsymbol{K}) + \vec{F} + \rho\vec{g} \tag{4}$$

where $\boldsymbol{K} = \eta\left(\vec{\nabla}\vec{u}+\left(\vec{\nabla}\vec{u}\right)^T\right)$, η is dynamics viscosity of air (Pa·s) , ρ is the density of air (kg/m^3) , $\vec{u}$ is a vector field velocity (m/s), p is a pressure (Pa), $\vec{F}$ is an external force density (N/m^3), $\boldsymbol{I}$ is an identity matrix, and $\vec{g}$ is gravitation field (m/s^2).

For the simulation, the surface of the acrylic tube was set to be a dielectric surface. Both applied voltage and ground were set on the surface of the electrodes. The recombination process of ions and the lost electron on the wall due to the collision was included as the boundary condition of plasma. All boundary surfaces were set to be sticky walls, so the smoke particles were trapped on the wall. The 2D simulation was considered and the phenomenon was analyzed only the cross-section of the tube which is shown in figure 2. The simulation results are shown in figures 3, 4, and 5 respectively.



(a) (b)

Figure 2. (a) Design of the simulation (b) Mesh of system used for finite element method.

2.2. Experiment method

For the experiment, a particle counter, as shown in figure 1, was used to detect the particulate matters which were emitted from a joss stick. The meter could count the particles whose sizes are 0.3 µm, 0.5 µm, 1.0 µm, 2.5 µm, 5.0 µm, and 10.0 µm. The smoke particles flowed through the electrodes which were connected to the high voltage AC power supply. The operating voltage was varied to 5 kV, 7 kV, and 10 kV. The numbers of the smoke particles were investigated for each different operating condition.

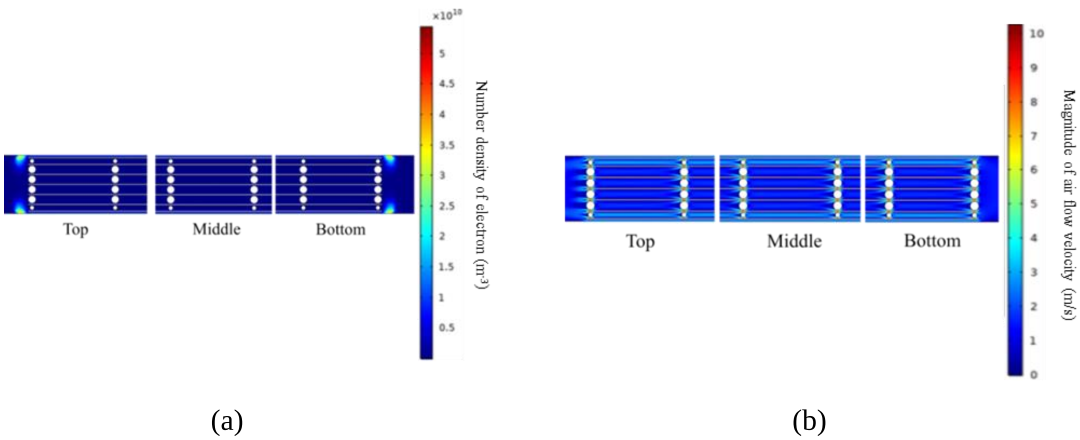


Figure 3. (a) Distribution of electron density of plasma from the simulation (b) Air flow velocity distribution obtained from the simulation.

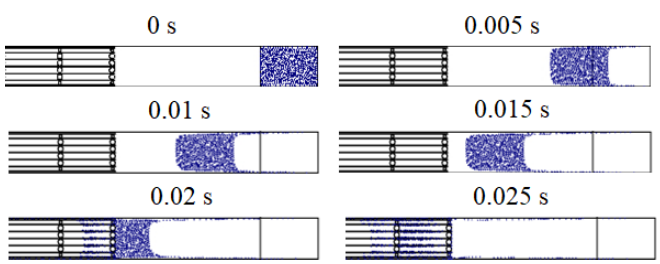
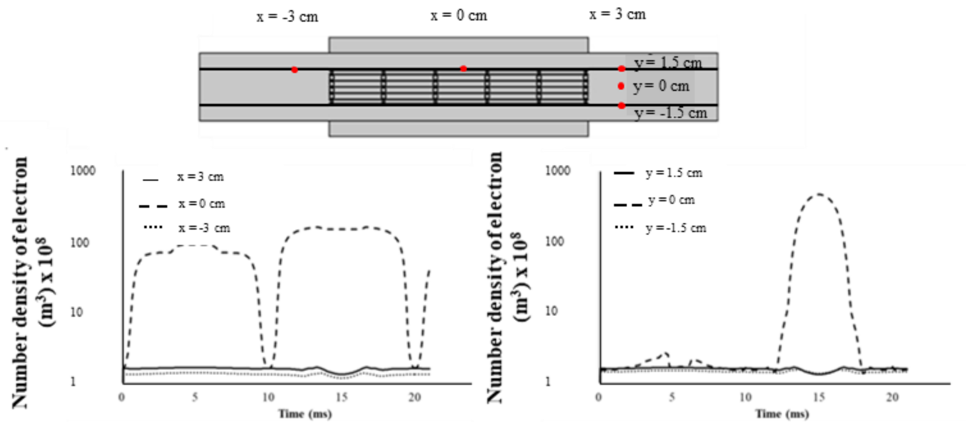


Figure 4. Picture showing simulated particle trajectories from the simulation.

3. Results and discussion

From the simulation, figure 5 shows a line plot of the relationship between the number density of electrons across the horizontal and vertical position of the tube. The number density varies with positions along the axis of the tube which has the maximum value of the number density at surfaces of the electrodes. The number density of electrons is homogeneous between the electrodes. In the vertical axis, the number density of electrons is the maximum at the center of the electrode. From this result, both electrons and ions suggested that they cause the change to the charge property of the particulate matters which are affected by the electric field between the electrodes. The particulate matter is trapped between the electrodes.



(a) (b)

Figure 5. (a) Number density of electron along horizontal axis varying with time (b) Number density of electron along vertical axis varying with time.

The relationship between the maximum number density of electrons and the operating voltage is plotted and shown in figure 6. The maximum number density also increases due to the increase of the operating voltage. The number of particulate matters detected under each operating voltage condition is compared to the number of the particles under non-operating voltage conditions. The percentages of the particles from various operating voltages are shown in table 1. From the experimental results, the percentage of detected particles decreases when the operating voltage is increased. Both particles with 1.0 μm and 2.5 μm in size were trapped the most in the system. However, most particles escaped when the operating voltage is the lowest at 5 kV. It is interesting to note that the plasma was not generated at an operating voltage of 5 kV. Since the particulate matter are not charged particles therefore it is not surprising that the electric field alone did not have any effect on these particles. In figure 6, it can be seen that there is increasing in the number of electrons when the operating is increased.

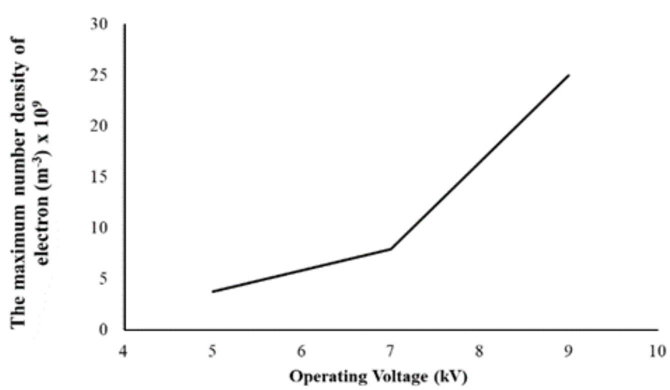


Figure 6. The relationship between the operating voltage and the maximum number density of electrons.

Table 1. The percentage of detected PM obtained by experiment under operating voltage.

Particle sizes (μm)	Percentage of detected particulate matters			Number of the counted particle under non-operating voltage
	Operating Voltage			
	5 kV	7 kV	10 kV	
0.3	96.05	19.76	13.22	774,194 ± 130,867
0.5	96.63	10.41	7.98	373,980 ± 29,523
1.0	100.00	6.99	6.27	67,814 ± 18,295
2.5	89.21	6.07	6.16	6,625 ± 4,071
5.0	93.38	10.55	9.03	443 ± 353
10.0	97.44	18.11	11.08	117 ± 96

From the simulation results and the experimental results, it can be deduced that particulate matter is affected by charged particles from the plasma. Electrons generated in plasma affect the charge property of the particulate matter and therefore they are moved by the electric force toward the electrodes. By increasing the operating voltage, the strength of the electric field is increased as well as raising the number of electrons. With both of these effects, the numbers of microparticles detected by the particle counter device are expected to reduce as shown by the result. The size of particles generated most from combustion is 0.3 μm. The smaller particles respond to the attractive force better than the bigger particle, so the particles that were trapped by the system are small in sizes which are 1.0 μm, and 2.5 μm.

In this work, we put our emphasis on the effect of plasma in trapping PM, in practice, the heating effect associate with plasma production must be considered. The effect of heat is not seen here as the operation is limited to a small time scale of 20 seconds. For longer operating time, materials with better heat tolerance that has similar dielectric property must be considered such as glass or quartz. Another important issue that must be considered for practical use is the cleaning process of the system which was not investigated here, but it is possible to design a cleaning cycle such that the PM is flushed out by clean air when DBD plasma is idle to a trapping water reservoir.

4. Conclusions

Dielectric barrier discharge plasma can trap smoke particles from a joss stick. The experimental results were confirmed by the result from the simulation. The dynamics of the plasma and the trajectory of particles were simulated by using the finite element method. The number of particles was measured by a particle counter. It was founded that;

(1) Increasing the number density of electrons and the strength of the electric field by increasing the operating voltage can cause the number of particulate matters to reduce. Both ionic charge and electron in the plasma could change the charge properties of the smoke particles. By rising the electric field, the electric force is increased which can attract charged particulate matters to the inner electrode.

(2) Sizes of particles that were the most affected were 1.0 μm, and 2.5 μm due to lower inertia.

Further work on system management, appropriate materials, and design are required for the practical implementation of this concept.

Acknowledgment
The authors would like to extend their great appreciation to the Plasma Technology and Nuclear Fusion Research Unit, Chulalongkorn University and College of industry technology, King Mongkut's University of Technology North Bangkok for initiating the plasma research for this work, and Navamindradhiraj University for their financial support.

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