A high voltage electrostatic filter for particulate matter PM$_{2.5}$ capture applied in motor vehicle exhaust system

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Abstract. Increasingly strict air pollution regulations along with global warming issue have peaked the interest in cleaner emission emitted by motor vehicle. In line with this, this study was aimed to develop a particulate filtering system based on an electrostatic principle for particulate matter with the diameter less than 2.5 μm, as known as a fine particle, and to test the performance of the filter. The filter consists of aluminum anodes and cathodes as the electrostatic electrodes. These electrodes were placed into the filter frame and installed on a motor vehicle muffler. The test was conducted to estimate the filter performance by measuring particle concentrations before and after using the filters. The filter was tested under four different electrostatic voltages: $V_1$ 100 Volt, $V_2$ 200 Volt, $V_3$ 300 Volt, and $V_4$ 400 Volt. The results show that the filter can reduce fine particle concentrations with the best efficiency of 50%, 60%, 62%, and 68%, respectively for $V_1$, $V_2$, $V_3$, and $V_4$. Filter performance was directly influenced by the applied voltage and the time of the test.

1. Introduction
Due to urbanization and globalization, the graph of environmental problems has been raised. There is a growing concern about the emission from many sources due to the climate change issue and their risk on health [1–3]. For example, increases in the motor vehicle usage decrease the AQI (air quality index), as described in the latest study [4,5]. Thus, in the air quality index, particulate matter with the various diameter can be found as the main type of traffic-related emission.

PM (Particulate matter) can be classified into some types in terms of their average diameters [6]. PM is a mixture of solid particles and liquid droplets in the air, having many sizes, shapes, and chemical compounds [7]. Ultrafine particle is a type of particulate matter having a diameter less than 0.1 μm and known also as PM$_{0.1}$ or nanoparticle [8]. PM$_{2.5}$, or fine particle, has an aerodynamic diameter between 0.1 and 2.5 μm [9,10]. PM$_{10}$, as known as coarse particle has a bigger aerodynamic diameter, less than 10 μm [3,11]. The biggest particulate matter is TSP (total suspended particle) having an aerodynamic diameter less than 100 μm, as the mixture of other types of particulate matters. Due to their different sizes, they have different physical characteristic, including different toxicity [3].

For the air quality managements, especially in metropolitan areas of Indonesia where the level of particulate matters have been surpassing limit values of WHO (World Health Organization) or the Indonesian Department of Health [12,13], a development of a filtration technology dealing with particulate matter concentration reduction is urgently required. That is why it is a need to propose a new and better filtration system. The objective of the developed technology is clearly to decrease or
curtail the particulate matter emission from motor vehicle with a reliable efficiency at the lowest cost of the development.

There are some common filtrations technology that has been developing to contribute to the AQI improvement, whether for an indoor or and outdoor condition. For examples, thin particulate matter filters made of coco fibers, water hyacinth, and banana leaf in a different density were a kind of fine particle filter that were developed for motorcycle exhaust system. These types of porosity-based filtration systems can reduce ultrafine and fine particle concentration with the efficiency more than 30% [14,15]. A higher removal efficiency (more than 90%) can be found in a transparent air filter, a porosity-based filter with a surface chemistry controlling [16]. However, it was an indoor air filter and did not recognized for outdoor use. Another study has demonstrated a cordierite DPF (diesel particulate filter) for a heavy duty engine, resulting lesser concentration of PM with a value well below 2010 EPA heavy duty regulation limit [17].

To realize a filtration system for motor vehicle exhaust is a need to develop a real filter that can be applied in situ. The filter should also has a high removal efficiency and be suitable for a real environment. So, in this study, a low-cost and a high voltage electrostatic-based fine particle filter was tested on an engine of motor vehicle. The effect of voltage variation on the filter was investigated, and the filter performance was evaluated.

2. Methods

2.1. Filter Development

The voltage source was generated from motor vehicle accumulator (DC 12 Volt) that was converted into a variable voltage source (DC 100 to 400 Volt). For the filter development, aluminum plates were used as the anodes and cathodes of the developed filter (thickness = 0.21 mm). These electrodes were separated by 14 mm to create a filter gap (d) related to the electrostatic principle (Figure 1). This value was chosen related to the dimension of the muffler diameter. The filter consisted of three sets of electrodes that were connected to a voltage source with a direct current. The voltage was varied into V1 (100 Volt), V2 (200 Volt), V3 (300 Volt), and V4 (400 Volt) in order to investigate the correlation between the applied voltage and the efficiency resulted by the filter.

\[ Ef = \left( \frac{\Delta C}{C_{in}} \right) \times 100\% \]  

(1)

Figure 1. The schematic of the tested filter.

2.2. Filter Performance

The filter performance was tested under laboratory test with standard room temperature. A motor vehicle sample was used as the source of the fine particles (particulate matter with the diameter less than 2.5 μm). This test was conducted for an hour with an interval time of 10 minutes. Fine particle concentrations before \( (C_{in}) \) and after \( (C_{out}) \) applying the filter were measured using a Kanomax Digital Dust Monitor Model 3443. The flow rate of the emission was measured using a Kanomax Anemometer Model A031 (Figure 2). To identify filter performance, a ratio percentage of the fine particle concentrations was calculated using the equation below [9]:

\[ Ef = \left( \frac{\Delta C}{C_{in}} \right) \times 100\% \]  

(1)
ΔC is the difference between $C_{in}$ and $C_{out}$ (mg/m$^3$).

**Figure 2.** Set-up of the fine particles concentration measurement.

2.3. **Statistical Analysis**

The results were expressed as mean±SEM (standard error of the mean). The difference between $Ef$ was analyzed using an analysis of variance test or ANOVA ($p < 0.05$ was considered statistically different [18]). The correlation between used voltage $V$ and $Ef$ was approached using a polynomial equation regression model ($R^2 < 0.80$ was considered strongly correlated).

3. **Results**

3.1. **Fine Particle Concentrations**

Fine particle concentrations of the measurements are listed in Table 1. Of the voltage variations, four results were found to have different results but in a similar decreasing trend. The concentrations were grouped into five categories: $C_{in}$, $C_{out V1}$, $C_{out V2}$, $C_{out V3}$, and $C_{out V4}$.

**Table 1.** Fine particle concentrations emitted by motor vehicle sample before and after using electrostatic filter ($n = 3$).

| Time (minute) | Fine Particle Concentrations (x10$^{-3}$ mg/m$^3$) |
|--------------|-----------------------------------------------|
|              | $C_{in}$          | $C_{out V1}$     | $C_{out V2}$     | $C_{out V3}$     | $C_{out V4}$     |
| 10           | 65±1             | 38±4             | 29±3             | 26±4             | 25±1             |
| 20           | 62±1             | 35±5             | 26±3             | 24±3             | 22±1             |
| 30           | 62±2             | 32±4             | 25±3             | 24±2             | 20±1             |
| 40           | 59±1             | 29±3             | 23±2             | 22±3             | 19±1             |
| 50           | 56±2             | 27±3             | 22±3             | 21±2             | 18±1             |
| 60           | 53±3             | 25±2             | 22±2             | 22±1             | 19±1             |

Table 1 shows that in this study, $C_{in}$ had the greatest fine particle concentration, followed by $C_{out V1}$, $C_{out V2}$, $C_{out V3}$, and $C_{out V4}$, All three repeated measurements have similar results ($p < 0.05$). In the first time interval, all categories show the decreasing trend. This trend continues until the last time interval. The values have shown that fine particle concentrations are generally high in the first time interval of the measurement, especially within the 10th and 20th minute. Moreover, fine particle emission decreases markedly in the 10th minute, and the largest decreasing point can be identified in $C_{out V4}$. 
3.2. Fine Performance

Figure 3 illustrates the filter performance for four different voltage tests: 100, 200, 300, and 400 Volt, respectively. It is seen that the efficiency is higher by the increasing time. This is because, at a longer time, the combustion rises up due to the higher engine temperature. The best efficiency is found in the middle measurement time (40th – 50th minute). On the 1st 10 minutes, the filter can reduce fine particle concentrations with an efficiency of 41% to 62%. These efficiencies increase significantly for about 4% to 9% after being used for about 30 minutes. V4 has 62% to 68% for the highest and the lowest filter efficiency, whereas V1 decreases fine particle concentrations with the efficiency of 41% to 50%. Similar trends in V2 and V3 are obtained at the 40th minute, in which having the peaks of the filter efficiencies (60% and 62%). Maximum filter efficiency obtained in this work indicates the saturated zone of the filter usage time. Moreover, V4 performed better than other voltages at all testing time. This may be due to higher electrostatic force \( F \) and electric field \( E \) of the filter, which improved the performance of a standard motor vehicle muffler, as described also in our previous study [19].

According to the research result, the filter can capture some of the fine particles emitted by the motor vehicle. Filter efficiency was influenced by the effect of the electrostatic capture mechanism as a substantial factor. In a constant flow rate (based on the anemomaster measurement), the increase in the voltage of the electrostatic filter gradually raised the charge level on the particles [20]. As described in the previous section, the highest voltage 400 Volt generates the highest filter efficiency, due to its highest electrostatic force \( F \) and the highest charge level \( Q \). With an increase in the electrode charge, the level of electrostatic capture mechanism also increases, which is more evident for the highest voltage 400 Volt (Figure 4). In all cases, the results indicate that the filter efficiency \( E_f \) is directly influenced by \( V \), since:

\[
V = E \cdot d \quad (2)
\]

With a constant \( d \), the only factor that influences \( E \) (electrostatic field) is \( V \). In addition, as expected for the highest \( V \), the result shows that the filter can decrease more fine particles (0.034 mg/m³ on the last measurement time). It is estimated that a higher \( E \) with a constant \( q \) (particle charge) favors a capture mechanism of fine particles, with a higher \( F \), since:

\[
F = q \cdot E \quad (3)
\]

\[
F = \frac{V \cdot q}{d} \quad (4)
\]

Figure 3 also shows the peak times of the filter efficiency, indicating the saturation of the filtration. In these conditions, the filter was considered dirty, as the maximum capacity of the filter in capturing fine particles. The trendline of the experimental results shows conformity with a theoretical prediction: the electrostatic surface area \( A \) will decrease due to the particle accumulation in a certain time \( t \). The only way to bring back the normal filtration capability is just by cleaning the surface of the filter, like a filter regeneration of a porosity-based particulate filter.
Figure 3. Filter efficiencies in the series of measurement times.

Figure 4. The correlation between voltage and filter efficiency at 10th minute (blue line) and 40th minute (green line), $R^2 > 0.80$.

We measured the flow rate of the emission before and after passing through the filter for approximately an hour of filtration to estimate the level of flow drop due to the filtration system. This test was also conducted in a filter without applying any voltage in it ($v_0$). In addition to the expected result of increasing the voltage, it can be seen that a lower flow rate occurred in a lower voltage. The mean value of $v_0$ as the control (5.55±0.01 m/s) shows no significant difference with the result
obtained in $v_1$ (flow rate of the usage of 100 Volt), 4.00±0.01 m/s. However, this value is lower than $v_2$ (flow rate on 200 Volt) and $v_3$ (flow rate on 300 Volt): 4.19±0.02 m/s and 4.21±0.01 m/s, respectively. As expected, the highest flow rate after using a filter is referred to $v_4$ (flow rate on 400 Volt), 4.37±0.02 m/s. According to these results, the flow drop of the filter is below 30% and not so sensitive to the variation of the voltage and particle charge level ($p < 0.05$).

4. Conclusion
The high voltage of the electrostatic-based particulate filter work well, considering the concentrations of fine particle before and after passing through the filter and the filter performance (efficiency). The increase of voltage is linearly correlated with the filter efficiency. As expected, the filter can reduce fine particles with quite high efficiency. The results show that the filter can reduce fine particle concentrations with the best efficiency of 50%, 60%, 62%, and 68%, respectively for $V1$, $V2$, $V3$, and $V4$. The filter performance was directly influenced by the applied voltage in all tested time.

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