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ULTRAFINE PARTICLE FILTER DESIGN FOR MOTORCYCLE EMISSION EXHAUST SYSTEM: A HIGH VOLTAGE ELECTROSTATIC-BASED SYSTEM

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ABSTRACT: A large number of motor vehicles in the world have been linked to the increase of the emissions, such as particulate matters and gases. These pollutants, especially for the particulate matters with the diameter less than 0.1 micrometer or ultrafine particles, become detrimental thing to the natural environment and human health. There is a need to develop a better method to decrease the particles. Thus, one step ahead of the technological improvement in the transportation sector is the development of an emission filter applied in a motor vehicle exhaust system. According to this background, we developed an ultrafine particle filtering system based on an electrostatic principle using a direct current - high voltage. The filter is based on a electrostatic principle by using uses aluminum as the anode and cathode. This filter was tested under the different DC voltage of 100, 200, 300, and 400 Volt. The efficiency of the filter was tested by measuring the motor cycle ultrafine particles before and after applying the electrostatic filter. The particle concentrations were measured by using a TSI P-Trak Ultrafine Particle Counter model 8525. The result shows that the designed filter works well in reducing the ultrafine particles., with the efficiency of 7% to 46%. The filter efficiency depends on the applied voltage.

Keywords: Efficiency, Electrostatic filter, Emission, Ultrafine particles

1. INTRODUCTION

The transportation sector has been growing from year to year. It is not only the developing technology, but also the motor vehicle usage in the world is increasing, as expected in Asian countries [1,2]. As the impact of this growing usage, the activity of transportation mode, especially for the motorcycle, exceeds the other kinds of motor vehicles. This phenomenon can be found in many big cities in the world, such as Hanoi, Jakarta, and Macao [3,4].

Besides, due to transportation sector activities using a motor vehicle, a large number of emissions accumulate and spread around ambient air. As confirmed in emission modeling, the emission is strongly related to vehicle number [5]. Furthermore, these emissions can be found as gaseous and PM (particulate matter) pollutants. For example, PM_{10} (particulate matter with a diameter less than 10 μm) with a high concentration of heavy metals (such as Ba, Fe, and Cu) can be identified in the area with a high traffic intensity [6]. Transportation sector also contributes to CO_2 (gaseous emissions), as the result of a combustion process [7]. As confirmed in the previous study of IEA (International Energy Agency), 23% of the total carbon dioxide emissions in the world was contributed by the transportation sector, including automobiles, light trucks, freight trucks, and buses [8]. A heavy duty vehicle such as bus can emit nitrogen oxides and $PM_{0.1}$ (particulate matter with a diameter less than 0.1 μm) with the emission factors up to 5 g/ km for nitrogen oxides and 0.001 g/ km for $PM_{0.1}$ [9]. A recent study also shows that vehicular traffic becomes a contributor to air pollution. It shows a high amount of CO_2, CO, NO, SO_2, and PM in which dominantly emitted by four-wheeler gasoline vehicles [10].

A proper approach to dealing with the motor vehicle emissions must be integrated with efforts to decrease the emissions. For an example, improving or mitigating motor vehicle emissions only in existing and future vehicles and traffic by improving engine efficiency and traffic management is not quite adequate to decrease the emissions in the ambient air. Selecting different fuels, or developing more efficient vehicle technologies or fuel additive also need more systems. Another proper approach is urgently needed.

One step of technological improvement in the transportation sector is the development of an emission filter applied in a motor vehicle exhaust system. This particulate matter filtration system can be found as an electrostatic filter, a radiation filter, and a porosity filter. The electrostatic principle is an electricity-based filtration system for reducing particulate matter, *i.e.,* a DPS (electrostatic diesel particulate matter filtration system) technology for a diesel heavy-duty vehicle exhaust system [11]. This kind of filtration technology had also been studied with a combination of a diesel oxidation catalyst and had been applied in non-road diesel machines [12]. In a motorcycle exhaust system, a porosity-based filter has been developed to reduce $PM_{2.5}$ emission with the efficiency of 35 – 64% [13]. Another study shows a significant performance (up to 24%) of a heat radiation-based filter when applied in a motorcycle exhaust system [14].

It is true that emission filter technology is a need to reduce air pollutant in ambient air, especially for the contaminant emitted by the motor vehicle. However, different sides must be taken into account when developing an exhaust emission filtration system. As an alternative approach, electrostatic principle has a high potential for the real application in decreasing motor vehicle exhaust emissions. This principle somehow needs less energy and budget. Moreover, the performance and application of electrostatic filtration system are relatively better than the other methods.

2. MATERIALS AND METHODS

2.1 Motorcycle Samples

A standard motorcycle (in good condition, no modification) was used as the ultrafine particles source. This motorcycle sample had an automatic transmission with the engine cubication of 125 cm^3. It used capacitor discharge ignition for the electronic ignition system and carburetor for the fuel supply system.

2.2 Filter Fabrication

The electrostatic filter (Fig.1) was made of aluminum plates that were consisted of anodes and cathodes. These electrodes were 1.4 mm apart (*d*). This filter gap was chosen due to the dimension of the motorcycle exhaust system. The filter probes were connected to the high voltage source with a direct current (DC).

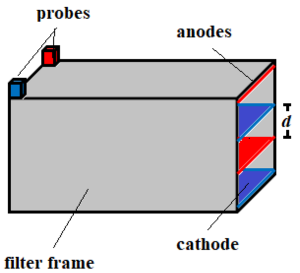

Fig.1 The schematic of the filter

This voltage was obtained by amplifying the standard accumulator voltage, 12 Volt DC, with a signal conditioning circuit (Fig.2). As the result, there were four different voltages to generate an electric field (*E*), with the variations of *V1* (100 Volt), *V2* (200 Volt), *V3* (300 Volt), and *V4* (400 Volt). Each voltage variation was applied to each filter to investigate the best efficiency.

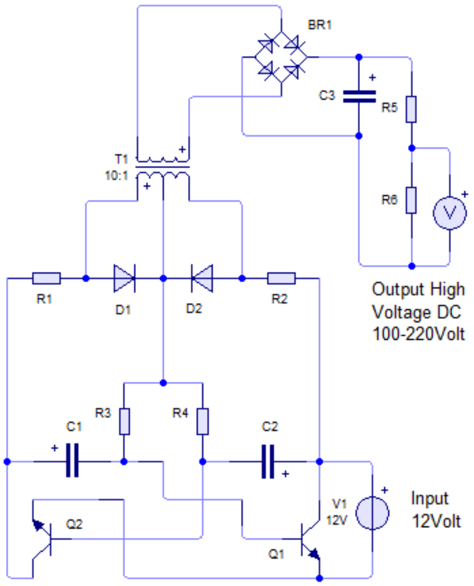

Fig.2 The schematic of the signal conditioning circuit

The signal conditioning circuit consists of a variable resistor to generate different voltage. A center tap transformator (T1) and 2N3055 transistors (Q1 and Q2) are used to amplify the input voltage (12 Volt) to 220 Volt AC (alternating current). Then, this resulted voltage is inverted using a diode bridge circuit (BR1). The output signal is filtered using an electrolytic capacitor (C2).

2.3 Filter Performance Test

Figure 3 shows the set-up of the filter performance test. Each filter was tested to investigate the filter performance related to filter efficiency (*Ef*) in reducing ultrafine particles concentration. This test was applied in the 125 cm^3 motorcycle sample for 60 minutes per voltage variation (with the interval time of five minutes) [13]. Ultrafine particle concentrations before (C_{in}) and after (C_{out}) applying the electrostatic filter were measured using a TSI P-Trak Ultrafine

Particle Counter, model 8525. The input and output emission temperatures (T_{in} and T_{out}) were measured using digital thermometers (with thermocouple type-K sensors). The flow-rate of the emission (v_{out}) was measured using a Kanomax Anemomaster, model A-031. The filter efficiency was calculated using Eq. (1) below [13].

$$Ef = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

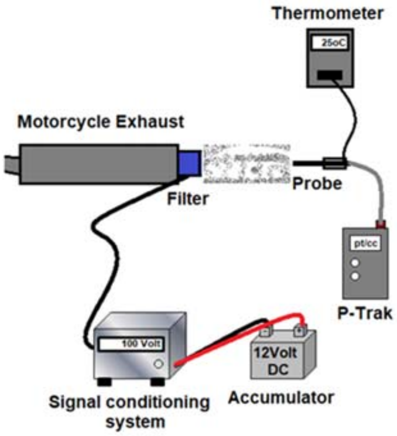

Fig.3 The set-up of the filtration test using motorcycle sample

2.4 Statistical Analysis

All recorded values were expressed as mean ± SEM (standard of means). The difference between filter performance was analyzed using an ANOVA (analysis of variance) test, in which $p < 0.05$ was considered statistically different. The correlation between applied voltage and filter performance was approached using a 2nd order of polynomial regression model, in which $R^2 < 0.70$ was considered correlated [15]. All statistical analysis was performed using Microsoft Excel 2016.

3. RESULTS AND DISCUSSION

3.1 Ultrafine Particles Concentration

The filters were installed on the motorcycle exhaust system in order to measure the ultrafine particle concentrations. These measurements were repeated three times for each voltage variation, *V1*, *V2*, *V3*, and *V4*. These measurements were done for 60 minutes for each measurement, with the interval time of five minutes. All results were shown in Table 1-2 below.

Table 1 Ultrafine particle concentrations before passing through the filters, C_{in}, from three times measurements (1st - 3rd)

Times (minutes)	Ultrafine Particles (x10^3 particles/ cm^3)		
	1st	2nd	3rd
5	18.5	18.2	18.2
10	18.5	18.4	18.5
15	18.4	18.1	18.4
20	18.4	19.3	18.2
25	17.5	20.2	17.7
30	17.8	19.5	17.6
35	17.7	18.2	17.8
40	17.6	16.9	17.4
45	17.4	16.7	17.2
50	17.1	17.2	17.4
55	16.8	16.7	17.3
60	16.1	15.7	17.1

Table 2 Ultrafine particle concentrations of the tested after passing through the filters, C_{out} (mean±SD)

t (min)	Ultrafine Particles (x10^3 particles/cm^3)			
	V1	*V2*	*V3*	*V4*
5	17.1 ± 0.5	16.5 ± 0.1	15.0 ± 0.5	12.6 ± 0.8
10	16.8 ± 0.3	16.1 ± 1.1	14.6 ± 1.2	11.1 ± 1.1
15	16.5 ± 0.7	15.6 ± 1.3	14.5 ± 1.3	11.2 ± 0.6
20	16.8 ± 0.9	15.4 ± 1.9	14.4 ± 1.9	11.4 ± 0.1
25	16.4 ± 1.3	15.3 ± 2.1	13.9 ± 2.1	10.4 ± 0.6
30	16.1 ± 0.9	15.2 ± 1.9	13.3 ± 1.9	10.4 ± 0.8
35	15.8 ± 1.1	15.2 ± 1.9	13.2 ± 1.9	10.0 ± 0.7
40	15.8 ± 1.4	14.8 ± 2.2	12.8 ± 2.2	10.0 ± 0.2
45	15.2 ± 2.0	14.9 ± 2.0	12.7 ± 2.0	10.0 ± 0.5
50	15.5 ± 1.3	14.9 ± 1.6	13.0 ± 1.6	0.9 ± 0.9
55	15.5 ± 1.3	14.6 ± 1.7	12.4 ± 1.7	0.9 ± 0.3
60	15.2 ± 0.8	14.6 ± 1.9	12.4 ± 1.9	0.9 ± 0.3

According to the results, the filters were tested under different voltage variation in order to investigate the influence of the high voltage level in the filtration system. On each measurement result, the ultrafine particle concentrations without filters had a similar trend, where the highest concentrations were obtained at the first minute (minute 5). Meanwhile, these concentrations decreased significantly in the last measurement time. Interestingly, the installed filters, with the used of voltage variations generated lower concentrations, compared to C_{in} (as seen in Table 2).

After using the filters, the ultrafine particle concentrations decreased significantly, compared to C_{in} ($p < 0.05$). These results were consistent for all voltage samples. According to Table 2, *V4* yields the lowest ultrafine particle concentrations. On each sampling time, *V4* emitted least ultrafine particle concentrations compared to *V3*, *V2*, and *V1*. The highest concentration in *V4* is 12.6±0.8 particles/ cm^3, in which this value is obtained from three repeated measurements. Meanwhile, the lowest concentration in *V4* is referred to minute 60 (last minute). These values are significantly different with the results yielded by *V1*, as the lowest applied voltage.

V1 has more ultrafine particle concentrations, compared to *V4*. The lowest ultrafine particle concentrations in *V1* is up to 15.2±0.8 particles/ cm^3. When we compare the values, the highest concentrations of *V4* is only 74% of the highest concentration obtained in *V1*. These results indicate that the applied high voltage influences the reduction of ultrafine particle concentrations emitted by motorcycle sample.

3.2 Filter Efficiencies

Having measured the ultrafine particle concentration, we compared the filter performance from the first minute (minute 5) to the last minute (minute 60). Statistically, there is a significant difference in filter efficiency, since $p < 0.05$ (illustrated in Fig.4). *V1*, as the lowest voltage, generates 7% to 12% of filter efficiency, in which the highest efficiency is obtained from the 30th minute. This result indicates that *V1* has a saturated trend in a half time of the measurement, indicating the saturated zone of the filtration performance.

The similar trend can be found in *V2* and *V3*. In *V2*, the efficiency is 9% in the first five minutes. This value increases until 17% in minute 30. After that, the performance was drop to 11% in the last minute after passing the saturated point. Compared to *V2*, *V3* has better efficiency. *V3* has 17% to 27%, 10% higher than *V2* and 15% higher than *V1*.

Meanwhile, the largest voltage *V4* has the best filter performance with the highest filter efficiency, 46% on the last minute (60th minute). From the graphic below (Fig.4), a different trendline can be identified, since the saturated point is not pointing the half-time (30th minute) of the measurement anymore. Statistically, the difference between each sampling time is shown by the *p*-value (*p*-value is less than 0.5). It shows that the filter performances are time-dependent and voltage-dependent.

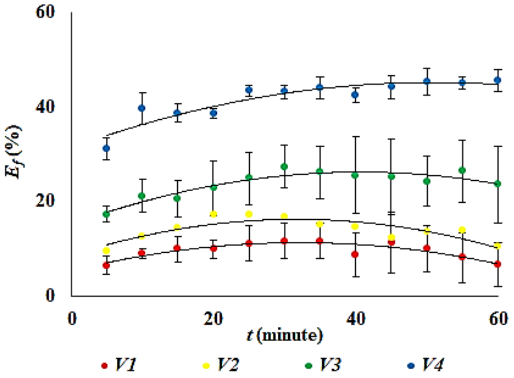

Fig.4 The association of applied voltages and filter efficiencies (mean±SD)

According to the measurement results, there is a little difference between emission velocity before and after passing through the filter. This value is not significant, since $p < 0.05$. However, a little change of emission velocity may indicate that there is no emission feedback to the engine due to the filter construction (filter blocking effect).

The filter performance is mostly influenced by the electrostatic force *F* and electric field *E*. In the electrostatic theory, voltage (*V*) is linearly correlated with the electric field, *E* (Eq. (2-4)). According to this theory, a higher electric field is caused by a higher voltage given.

$$E = \frac{V}{d} \tag{2}$$

so:

$$V = E\,d \tag{3}$$

and:

$$E = \frac{F}{q} \tag{4}$$

As the impact, *V4*, as the highest voltage, has the highest *E*. Meanwhile, the lowest voltage *V1*, has the lowest *E*. According to Eq. (4), *E* is linearly correlated with force *F*. That is why, by using a constant filter gap (d = 1.4 cm), the value of *F* is only influenced by the used *V*. As espected, we found that the correlation between the applied voltage and filter efficiency was positive linear, as the usage of a constant filter gap ($R^2 > 0.89$).

Based on the calculation, the electric field of the filters is in the range of 7.14 x 10^3 N/C to 28.57 x 10^3 N/C. The highest electric field is referred to 400 Volt, *V4*, while the lowest one is referred to the lowest voltage used, 100 Volt (*V1*) Fig.5.

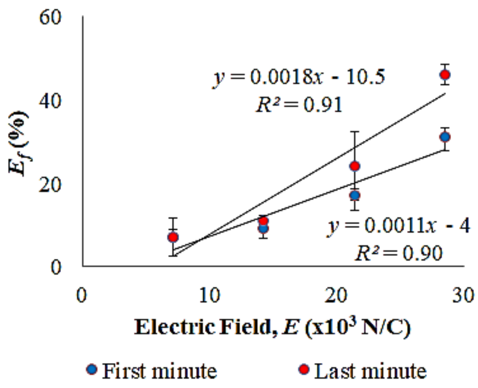

Fig.5 The association of electric field and filter efficiency (mean±SD)

In the case of time-dependent ant the influent of engine temperature (T_{eng}), a longer time means that more fuels (m) are used to produce energy. As a fundamental law, energy is neither created nor destroyed, and it only changes its form. As a consequent, many formulas of energy exist. Thus, this energy can be found as thermal energy (Q) and other forms of energies, where:

$$Q = m\,c\,\Delta T \quad (5)$$

Based on Eq. (5) above, it is shown that Q depends on fuel consumption in the quantity of mass, m, with a constant c (specific heat). A higher heat Q means that the change of temperature (ΔT) is also higher. According to the previous studies, the time of motorcycle warming up process may influence the engine temperature T_{eng}. In an idling and static position (1000 RPM, cold start of warming up), we found that a longer time (t) generated a higher engine temperature [16,17]. This term may impact the increase of output emission temperature, since the emission flows are laminer inside the system. This increase is linearly correlated with the increase of time and engine temperature.

4. CONCLUSION

This paper integrates high voltage DC electricity with electrostatic principle to decrease the ultrafine particle concentrations of motorcycle emissions. An electrostatic-based filtration system is adapted to capture the particulate matters with the diameter less than 0.1 μm emitted by the motorcycle exhaust system. The high voltage variations, 100 Volts to 400 Volts DC, enable to estimate emissions decreasing due to the applied voltage. According to the results, a higher voltage generates a higher filtration performance. The highest efficiency, 46%, is obtained from 400 Volts DC. Meanwhile, the lowest voltage, 100 Volts DC, generates the lowest filter efficiency, 7%.

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