Developing of Particulate Matter Filtering System for Motorcycle by Reusing Engine Thermal Energy Emission

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Developing of Particulate Matter Filtering System for Motorcycle by Reusing Engine Thermal Energy Emission

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Abstract. Vehicle particulate matter emission in terms of $PM_{0.1}$ and $PM_{2.5}$ have significantly increased their role in morbidity and mortality. In this research, we have developed a new method for particle matter filtering system to reduce the particulate concentration by optimizing the released combustion energy in the exhaust system. We reused the released energy to reduce particle emission by placing a metal net made of different materials such as aluminum, brass, stainless steel, and nickel in the compartment of the exhaust system. The system generated a radiation energy used to reduce particle concentration. The filter efficiency depended on the filter net material. The filter net made of aluminum gave the highest efficiency in reducing particle emissions. The efficiency reached 55% for the $PM_{2.5}$ and 46% for $PM_{0.1}$.

1. Introduction

Particulate matters or particles mostly are from natural sources such as fire forest or dust storm [1]. Moreover, industrial process [2] and vehicles usage [3] have contributed significantly in addition to particles in the air. Industrial particle emissions affect directly into the human health especially for people living in the range of the exposure area [4,5]. Meanwhile, vehicle particles widely affect the people living close to road and motor users [6].

The motorcycle is one type of motor vehicles commonly used in developing countries. The number of motorcycles has increased extensively in the last decade [7–9]. Motorcycle particles have been reported increasingly in the ambient air [10]. In the previous research, there was shown a relation between the motor vehicle usage and the particle concentration [11]. This result brought bad news for the human by the fact that the particles are very dangerous especially for the health [12]. Motorcycle particles are produced by the incomplete burning process of the fuel [13,14]. The particles are in different size distribution and chemical substances [6,15,16]. The particles have the ability to move freely in the air, increase the health risk [17,18], and penetrate in cellular level [19] and into a human through the skin via intracellular process [20] . Even though, the particles were found to have an ability to infiltrate into human cardiovascular via respiratory system [21-23]. A variety of health problems due to vehicle particle emission has been reported in the previous studies [24-27].

Reducing motorcycle particles has been attempted in the past decade. Various methods have been developed and tested in order to reduce the concentration. Planting of trees in the roadside is the common method to reduce ambient particles [28,29]. Another method was conducted by improving the engine capability to burn the fuel more efficient [30-32]. The exhaust filtering system has been developed for gas emissions [33-35]. Exhaust filtering system has limited to particle emissions because

of high particle concentration leading to the filter saturation that increases a risk of the filter or even the engine damage [36].

The latest particulate filtration technology has been developed in the diesel vehicles known as diesel particulate filter (DPF) [37]. The developed filter based on a porosity filtration to reduce the particulate matters [38]. This technology has been known to have a high efficiency but lack of the regeneration process [39]. In the previous study, the soot loading was found to affect the filter performance [40,41]. In addition, the regeneration cost was high and had to the difficulties in the process [39,42,43]. In this study, we propose a new filtration technology by reusing thermal energy released by the engine. The thermal energy is used to reheat the particulate emission to reduce the $PM_{2.5}$ and $PM_{0.1}$ concentration.

2. Method

2.1. Filter Material

The filter contains of a net ring made of metal such as aluminium, brass, stainless steel, and nickel that is placed on a compartment connector pipe in the exhaust. The net is clammed to fit on the pipe, The heat emission is transferred to the filter to generate a radiation heat. The net was arranged with the hole area of 2.0 mm^2 as seen in Fig 1.a. The filter was tested by placing at the P1 position (see Figure 2.a). We measured the temperature in the position before and after putting the filter. The measurement was conducted while the engine was on for 5 minutes. We conducted this procedure for all filter. The filter made of aluminium gave the highest temperature increase of 20.9 °C, meanwhile, the filter made of stainless steel, nickel, and brass increased the temperature of 16.0 °C, 15.2 °C, and 16.0 °C representatively. Based on this result, we preferred aluminium as the filter material.

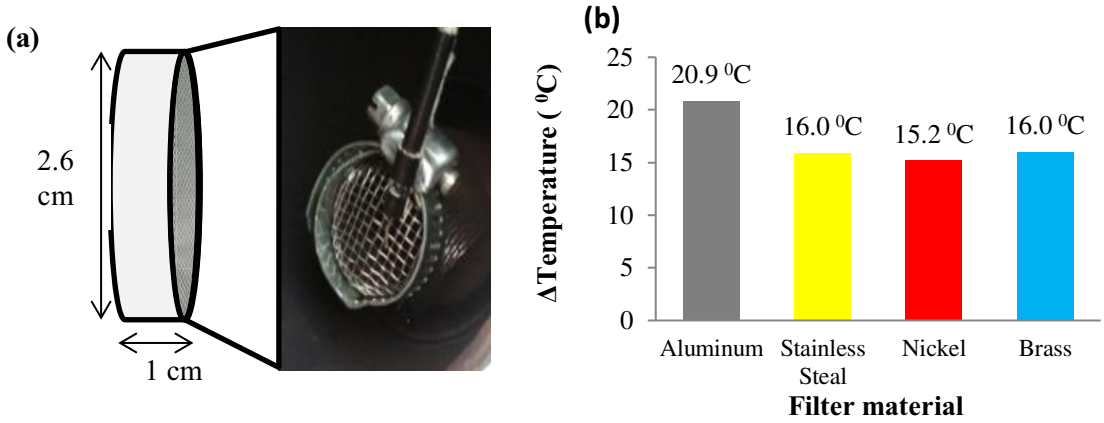

Figure 1. (a). The Structure of the filter. (b). The measured temperature after putting the filter made of different material.

2.2. Filter Position

In order to find the best position to get the highest temperature increase, we placed the filter in the position of P1, P2, P3, and P4 at the compartment in the exhaust as seen in Fig 2.a. The heat emission flows from the engine to the exhaust. In the exhaust, the heats pass through the first compartment, then goes to the third compartment, and finally reach to the second compartment before it releases to the air. Fig.2.a. illustrates the emission flow inside the exhaust. The flow direction is shown by the red arrow. The temperature measurement was carried out at the points with the high increase of 68.1 °C was found at the point of P1 while the temperature at the point P2, P3, and P4 was measured of 57.1^0 C, 42.3 °C, and 52.3 °C respectively. Based on this result, we determined the best position to place the filter at the point of P1.

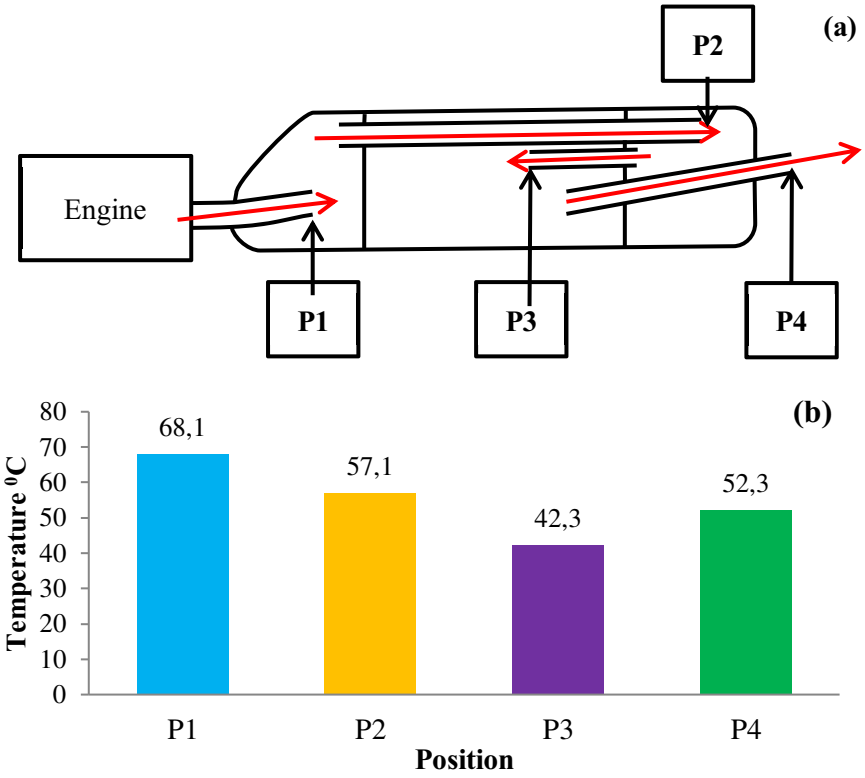

Figure 2. (a). The exhaust system schematic and the temperature measurement point. The arrow shows the smoke flow direction. (b). The measured temperature at the P1, P2, P3, and P4.

2.3. The Particulate Measurement

In order to test the filter performance, we measured the $PM_{2.5}$ and $PM_{0.1}$ concentration before and after the filter was fit on the exhaust The $PM_{2.5}$ was measured in mass concentration (mg/cm^3) while the $PM_{0.1}$ in particle concentration (particles/cm^3). The motorcycle $PM_{2.5}$ (Fine Particles) and $PM_{0.1}$ (Ultrafine Particles) was measured by using *Kanomax* dust monitor types 3443 and a P-track Ultrafine Particle Counter type 8525. The measurement was conducted by positioned the inlet of the measurement devices in the approximately 20 cm in front of the exhaust [44]. The motorcycle was settled at zero throttle condition to avoids driving style, road condition [45], and engine load [46]. The system temperature was also monitored during the concentration measurement. The measurement was done for the motorcycles for both configurations; standard exhaust and exhaust with the proposed system applied. The data sampling was taken in every 5 minutes for 25 minutes. The system efficiency was observed by compare the emission for both configurations uses Eq.1[44].

$$ef = \frac{Pc(f)}{Pc} \text{x } 100\% \quad (1)$$

ef is the system efficiency, $Pc(f)$ is the concentration of both particles after the system applied, the Pc is the particle concentration for standard configuration..

3. Result

3.1. The temperature level and the particle concentration in the exhaust system

Table 1 presents the average and deviation standard of the exhaust temperature, $PM_{2.5}$ and $PM_{0.1}$ concentration measured every 5 minutes. The temperature increases for the longer engine operated. When we turned on the motorcycle engine, the temperature was 68.0 °C, it increased to 76.0 °C in the minute of 25th. Meanwhile the $PM_{2.5}$ and $PM_{0.1}$ concentration decrease with the increasing temperature. The measurement at the minute of 5th, the $PM_{2.5}$ concentrations is 22.9 x 10^{-3} mg/cm^3 it becomes lower to 17.1 x 10^{-3} mg/cm^3 at the 25th minute. The similar result that it can be seen for the $PM_{0.1}$ concentration is 48.3 x 10^3 particle/cm^3 for the 5th minute, and it became lower to 37.2 x 10^3 particle/cm^3 at the minute of 25th. The trend of the temperature and the particle concentration measured at the variation of time, are shown in Figure 3a and 3b. Figure 3.a shows that the temperature increases when the engine was operated for a longer period. Meanwhile increasing the temperature causes both particle concentration of $PM_{2.5}$ and $PM_{0.1}$ decrease as seen in Figure 3b. The relationship between the particle concentration and temperature fits as the exponential equation of $C = 24.1e^{-0.087(T)}$ with the R^2 of 0.97 for $PM_{2.5}$ and $C = 51.58e^{-0.063}$ with the R^2 of 0.99 for $PM_{0.1}$.

Table.1. the average and deviation standard of temperature, $PM_{2.5}$ concentration, and $PM_{0.1}$ concentration measured every five minutes at the exhaust before applying the filter.

Measurement time (Minute)	Temperature (°C)	Concentration	
		$PM_{2.5}$ x 10^{-3} mg/cm^3	$PM_{0.1}$ x 10^3 particle/cm^3
5	68.0 ± 1.00	22.9 ± 0.70	48.3 ± 1.52
10	72.0 ± 1.00	20.4 ± 0.40	45.0 ± 2.21
15	73.0 ± 2.50	19.1 ± 0.50	43.3 ± 1.81
20	74.0 ± 4.50	17.7 ± 0.50	40.2 ± 1.12
25	76.0 ± 5.60	17.1 ± 0.40	37.2 ± 0.45

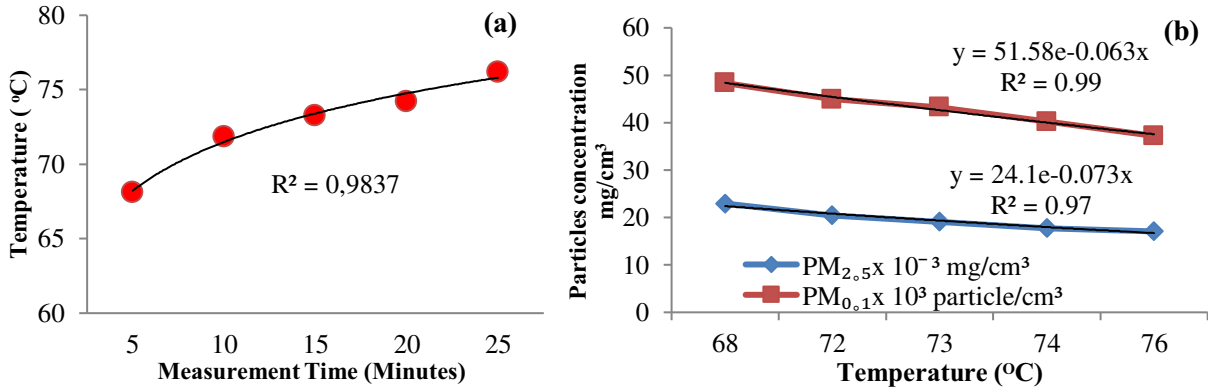

Figure 3. (a). The temperature increases as a function of time. (b). The particulate concentration decreases as a function of time.

3.2. The temperature increases after the filter applied in the conventional exhaust model

Based on the results that are stated in the previous experiment about the best filter material and position, we determined that the filter that was built from aluminum and was positioned in the P1. In the result, we observed the increasing temperature up to 89.0 °C in five minutes. The temperature increased consistently on the 25-minute measurement. The temperature increases logarithmically following the equation of $\Delta T = 7.37 \ln(t) + 8.95$ with T is the temperature's different and t is the

measurement time in minutes. The correlation factor between the temperature and the time is found higher than 0.9 that indicates a strong association between them. The complete measurement result is presented in the Fig 4.

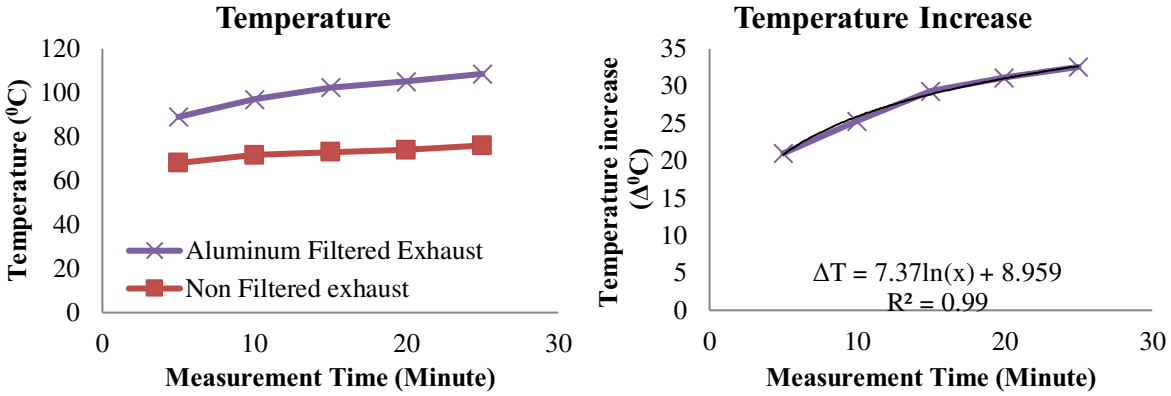

Figure 4. The temperature increases when the filter was placed in the exhaust system. The temperature change follows a logarithm function by $R^2 > 0.9$.

Figure 5 shows the concentration of $PM_{0.1}$ and $PM_{2.5}$ measured when the exhaust was with and without a filter at the different measurement time. In the fig.5, the *Wf* bar is the concentration of the particle before the filter applied and the *Fa* bar is the concentration after the filter applied. By putting the filter in the exhaust, we find the decreasing of the particle concentration of 9.75 x 10^3 particle/cm^3 in average for $PM_{0.1}$ and 16.86 x 10^{-3} mg/cm^3 for $PM_{2.5}$.

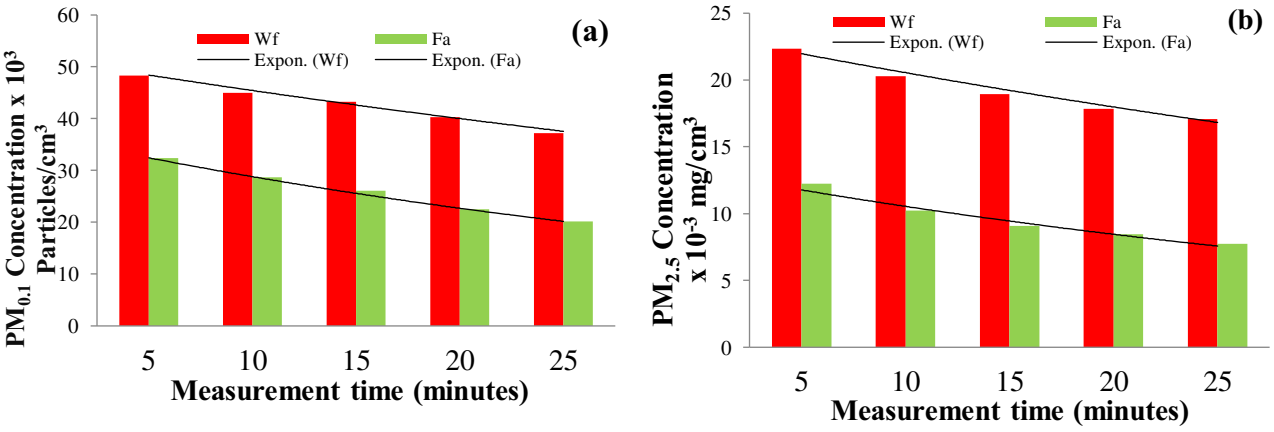

Figure 5. The $PM_{0.1}$ (a) and $PM_{2.5}$ (b) concentrations before and after putting the filter in the exhaust for different measurement time.

In table 2, we see the concentration change by temperature increase. In the table, we present the different temperature with and without the filter as Δ temperature. Based on the table, we find that in every temperature increase of 1°C, the $PM_{0.1}$ concentration decrease to 1.00 x 10^3 particle/cm^3 and 0.49 x 10^{-3} mg/cm^3 for the $PM_{2.5}$ concentrations.

3.3. The effect of temperature change

Regarding to the temperature increase that is related to the change of the particulate concentration, we plot the measured concentration of $PM_{2.5}$ and $PM_{0.1}$ concentration versus the temperature increase as presented in Fig.6. We find that the particulate concentration reduces exponentially for the higher temperature. The concentration reduction fit to the equation of y = 2.250 x 10^2 $e^{-0.018(T)}$ for $PM_{0.1}$ with

the R^2 of 0.89. Meanwhile, the relationship between the $PM_{2.5}$ and the temperature is found to follows $y= 2.077 \times 10^2 e^{-0.033(T)}$ with the R^2 of 0.99. This R^2 shows that the particulates concentration is strongly correlated by the emission temperatures.

Table 2. The increase of the temperature, $PM_{2.5}$, and $PM_{0.1}$ concentration is presented as a function of time.

Measurement time (Minute)	Particle Concentration		
	Δ Temperature (^{0}C)	Δ $PM_{0.1}$ x 10^3 particle/cm^3	Δ $PM_{2.5}$ x 10^{-3} mg/cm^3
5	16.7	16.0 ± 1.87	10.10 ± 0.92
10	18.8	16.3 ± 2.65	10.07 ± 0.29
15	21.4	17.2 ± 3.38	9.87 ± 0.44
20	22.0	17.7 ± 3.58	9.37 ± 0.49
25	22.0	17.1 ± 2.04	9.33 ± 0.14
Average reduction / 1^{o}C		0.84 ± 0.07	0.48 ± 0.08

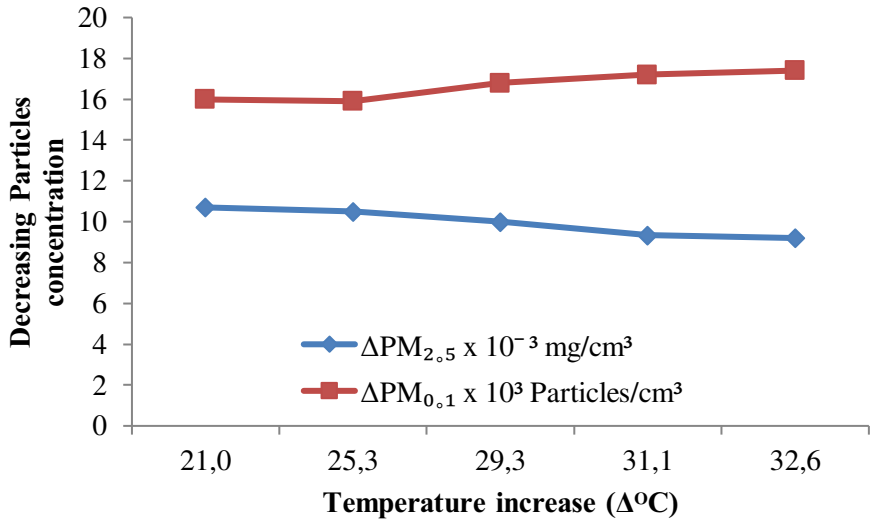

Figure 6. The relation between PM0.1 and PM2.5 concentration change versus the temperature increase.

3.4. The filter efficiency in the reduction of $PM_{2.5}$ and $PM_{0.1}$ concentration

In table 3, we present the filter efficiencies of the particulate concentration reduction. The filter efficiency is high for the temperature increase. At the temperature of 84.8 °C, the filter efficiency is found of 45% for PM2.5 and 33% for $PM_{0.1}$. When the temperatures increase to 90.7°C, in which the temperature arises to 5.9 °C, the filter efficiency is calculated of 5% for $PM_{2.5}$ and 3% for $PM_{0.1}$. When the temperature increases to 94.7 °C, the efficiency becomes larger to 2% for $PM_{2.5}$ and 4 % for $PM_{0.1}$. The efficiency rises to 1 % in for $PM_{2.5}$ and 4 % for $PM_{0.1}$ when the temperature is at 96.2 °C. Finally, at the temperature of 98.2°C, the efficiency is 2 % for both the $PM_{2.5}$ and $PM_{0.1}$.

Figure 7 a shows the temperature and the filter efficiency in reducing the concentration of $PM_{2.5}$ and $PM_{0.1}$ at the different duration of the operating engine. It indicates that when the motor engine is operated for a longer time, the exhaust temperature increases. As the result, the filter reduces the particle concentration with the higher efficiency. In order to find the correlation between the exhaust temperature and the filter efficiency, we plot the temperature versus the filter efficiency as shown in Fig.7.b.

Table.3. The filter efficiency of the $PM_{2.5}$, and $PM_{0.1}$ concentration is present as a function of temperature.

Temperature (°C)	Temperature Increases (Δ°C)	$PM_{2.5}$ Efficiency (%)	$PM_{0.1}$ Efficiency (%)
84.8	21.0	45.0	33.0
90.7	25.3	50.0	36.0
94.7	29.3	52.0	40.0
96.2	31.1	53.0	44.0
98.2	32.6	55.0	46.0

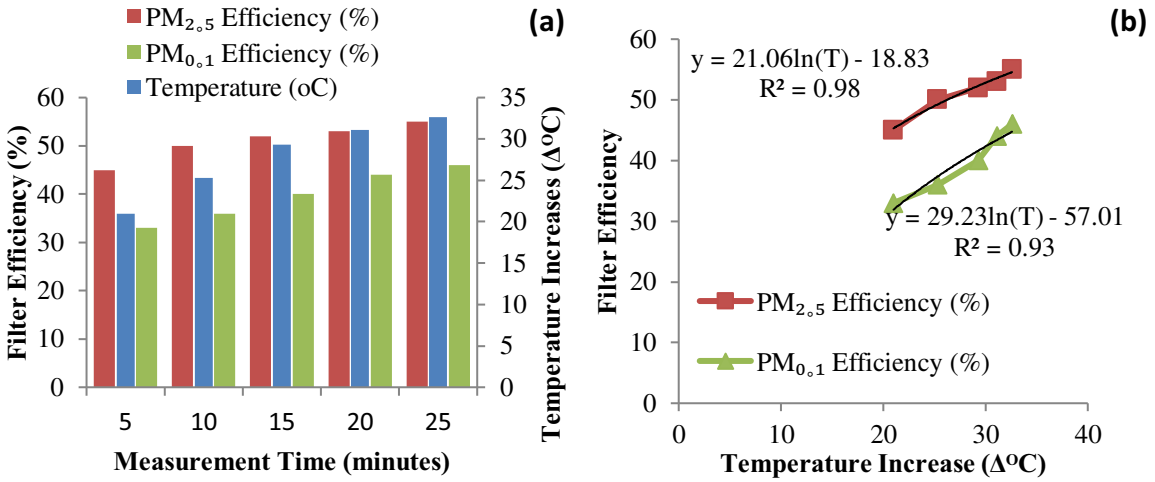

Figure 7. (a) The exhaust temperature, $PM_{2.5}$ and $PM_{0.1}$ efficiency at the period of the operating engine. (b) The $PM_{2.5}$ and $PM_{0.1}$ efficiency versus the exhaust

The efficiency of the filter is found to follows the equation y = 21.06 ln (T) – 18.83 in the $PM_{2.5}$ reductions. The R^2 in the $PM_{2.5}$ filtrations is calculated of 0.98. For the $PM_{0.1}$, the filter efficiency is observed to follows the y = 29.23 ln (T) + 57.01 with R^2 equals to 0.93. We calculate that the filter capability in reducing the particle emission with the efficiency of 0.77 % per $1\ ^0C$ for $PM_{2.5}$ and 0.92 % per $1\ ^0C$ for $PM_{0.1}$. It means for every increasing $1\ ^0C$ of the exhaust temperature can reduce $PM_{2.5}$ of 0.77 % and $PM_{0.1}$ of 0.92 %.

4. Discussion

Particle emission can be formed in the several ways. In the relation to this study, particles are formed by the fuel combustion in the engine chamber [47]. In the engine, the fuel is injected into the combustion chamber together with the air before igniting in a high compression level [48]. The result is a very high kinetic energy that is used to push the piston and to move the vehicle [49]. The combustion process results in the emissions (gas and particles) and thermal energy as the products. In the other word, the thermal energy leaves the engine through a convection process. The exhaust system such as a muffler or a silencer that is made of metal is used to absorb the thermal energy. Consequently, the emission eventually loses their temperature and become a cooling down [50]. This process leads to develop the secondary particles. Applied the metal net is found to increase the engine temperature logarithmically. The logarithmic function is caused by the metal thermal saturation characteristic [51].

In this study, we applied the metal net as a filter that increases the temperature through radiation process when it is passed by the convective thermal energy released by the motor engine. The increasing the thermal radiation energy is shown by increasing the temperature. The metal net enlarges

the radiation area and raises the surrounding temperature [52]. The radiation thermal energy may reduce a particle nuclei radius [53]. The consequence of the temperature increase is the particle concentration becomes to less in the amount.

Motorcycle produced emission in various formation. The previous study shown that the vehicle emission consisted of at least three forms of the substance; a gas, a very small solid substance known as particulate matter, and a droplet that is formed by the hygroscopic materials [54-56,57]. In the measurement, the droplet and the particulate matter is un-separated from each other [58]. During the reheating process, the filter increases the emission temperature. The engine's heat flows in the exhaust through two kinds of mechanism such as conduction and convection [59]. In the conduction scheme, the heat flows in the exhaust metal into the net, increases the net temperature. In the convection, the heat is released as the motorcycle emission together with the gaseous and particulate emission that is captured by the net. Both scheme caused the net temperature increase up to 100^{o}C by depends on the net position and material. The metal net acts as the thermal conductor that radiated the heat into it surround[60-62].

The motorcycle particulate emission concentration is strongly affected by the system temperature. The motor emission temperature increases when the emission flowed into the radiation area. The application of the metal net filter results in increasing the system temperature. The temperature increase is high enough to evaporate the droplet particulate matter into gaseous pollutant [63-65]. This behavior is initiated by the droplet composition that is built from hydrogen series [66-68]. The droplet deformation resulted in the particulate matter concentration reduction that is found in our experiment.

In this study, the reduction of particles is found differently depending on the size. We have the $PM_{0.1}$ concentration become less to 0.92 % for every the temperature increase of 1 ^{0}C, meanwhile, the $PM_{2.5}$ concentration reduces to 0.77 % for every the temperature increase of 1 ^{0}C. The increasing temperature may also use to burn the particle emission. Smaller particles are more easy to burn while the droplet may evaporated by in the higher temperatures [69-73].

The different size of particulates reduces exponentially by the increasing temperature. The particulates matters consist of liquid and solid that suspends in the air. Increasing the emission temperature causes the liquid content of particulate matters that may evaporate or the size change into the smaller particulates. As the result, the particulate matter concentration reduces. However, the temperatures that only increased bellows 100^{o} C may not high enough to reduce the PM in the solid form.

5. Conclusion

Developing a filtering system by applying a metal net to use the released thermal energy in the motorcycle exhaust, shows a very promising potential technique in reducing the $PM_{0.1}$ and PM $_{2.5}$ emission. The reduction of the particulate matter emission is significantly related to the temperature increase. Meanwhile, the filter efficiency depends on the metal used. The filter made of aluminum is found to have a good capability in reducing the $PM_{2.5}$ concentration of 0.77 % for 1 ^{0}C temperature increase and 0.92 % $PM_{0.1}$ concentration for every the temperature increase of 1^{0}C respectively.

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