**AEC0018**

# Effect of Palm Methyl Ester Blends Diesel on Small CI Engine Particulate Matter Quantity and Nanostructure

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***Abstract***

Compression Ignition (CI) Engine is popularly used in vehicles due to high thermal efficiency. However CI engine has a particulate matter (PM) problem which palm methyl ester could be one of possible solution to solve this problem. This research focuses on measuring the quantity, size, size distribution and nanostructure of particulate matter in single cylinder CI engine. Particulate matter quantity was collected by opacity smoke meter then captured the nanostructure image by using scanning electron microscope (SEM). The fuels chosen were commercial diesel (B7), blends of 20%, 40%, 60%, 80% and 100% of biodiesel by volume. For quantity and nanostructure analysis, five engine speed modes which consist of 1600, 1800, 2000, 2200 and 2400 rpm were applied on this research. At each engine speed, engine torque were varied with unload, 20%, 40%, 60% and 80% of maximum torque. For particulate matter size and size distribution measured by using laser diffraction technique with same fuel types at 80% load and 2400 rpm. The experimental results indicated that particulate matter quantity decreased when the concentration of biodiesel was increased in blend due to the impact of effective oxygen to more completely combustion. The lowest amount of particulate matter was recognized at 1800-2000 rpm caused by the best engine specific fuel consumption. In addition, when operating at high engine speed, particulate matter was increase because of shorter oxidation time in combustion period. The results of this research might be used as basic information for design and development of Diesel Particulate Filter (DPF) configuration for biodiesel blends diesel CI engines.

***Keywords**:* Biodiesel, Biofuel, Particulate matter, Soot, Emission

## 1. Introduction

CI engine is widely used in many application such as agriculture and transportation. Nowadays the energy demand is raising each year but petroleum has limited amount. It makes the price of fuel rapidly increase. Engineers and scientists have to find the alternative fuel which can be used in the standard engine with lower emissions.

In CI engine, the serious issues is the particulate matter (PM) and nitrogen oxide (NOx). The pollutants should be removed from exhaust gas because they affected environment and human health such as lung cancer.

The nanostructures of soot primary particles have been characterized using scanning electron microscope (SEM) and transmission electron microscopy (TEM) to understand them in detail. The mean diameter of the single primary and agglomerated particles is usually in the range of ultrafine particle (<100nm) and fine particle (<2.5µm), respectively [1-19]. The composition of PM from a diesel engine may vary widely depending on the operating conditions and fuel composition. PM is traditionally divided into three main fractions: solid fraction (SOL), soluble organic fraction (SOF), and sulfate particulates (SO4) that consist of sulfuric acid and water. The SOL of diesel PM is composed primarily of elemental carbon, sometimes referred to as inorganic carbon. This carbon, not chemically bound with other elements, is the finely dispersed carbon black or soot substance responsible for black smoke emission. Hydrocarbons (HCs) adsorbed on the surface of the carbon particles are presented in the form of fine droplets from the SOF of diesel particulates. At times, this fraction is also referred to as the volatile organic fraction (VOF). The SOF fraction contains most of the polycyclic aromatic HCs (PAHs) and nitro-PAHs emitted with diesel exhaust gases. PAHs are aromatic HCs with two or more benzene rings joined in various forms that are more or less clustered. These require special attention because of their mutagenic and, in some cases, carcinogenic character [9–14].

Nowadays applications of biofuels is a widespread means to reduce amount and particle size of regulated pollutant emissions produced by internal combustion engines because oxygen atoms inside fuel molecules promote more completed combustion, as well as to reduce the greenhouse gas resulting from carbon neutral. The combustion of bio-oxygenated fuel emits carbon dioxide (CO2) to the atmosphere for the growth of plants, which are produced by biodiesel fuel and released out of the atmosphere as carbon by photosynthesis. More advantages of biodiesel over other fuels are that it contains much lower sulfur and aromatic HC content [15, 16].

The objective of the present research is to investigate the impact of biodiesel fuel on morphology and quantity of biodiesel particulate matter by using opacity smoke meter and electron microscopy for better understanding and future design of diesel particulate matter configuration for biodiesel blends diesel engine application [17].

## 2. Experimental Setup and Method

### 2.1 Fuel properties

The fuels chosen in this experiment has six fraction of biodiesel. Commercial grade diesel (B7) and Biodiesel (biodiesel: B100-TIS2313-2549) was used as substrate for another fuel which has 20%, 40%, 60%, and 80% of biodiesel by volume called B20, B40, B60, and B80 respectively. The properties of substrate fuel has shown in "Table. 1". For fuel property of B20 to B80, heating value and density were estimate by interpolation between diesel and biodiesel.

Distillation curve "Fig. 1" below shows the relationship between temperature and percentage of fuel volume which change from liquid to gas phase. Biodiesel is more homogeneous fuel which shown by vaporize temperature. It is very narrow around 340 to 350 degree Celsius. When compare with conventional fuel, biodiesel has higher vaporization temperature due to heavier atomic weight and higher density [Table.1] so the heat of vaporization of biodiesel should be higher than conventional diesel.

Table. 1 Properties of commercial biodiesel fuel derived from palm-olein (biodiesel: B100)

| | Diesel | Biodiesel |
|---|---|---|
| Density (kg/m$^3$) | 844.78 | 864.4 |
| Cetane Number | 55 | 70 |
| Viscosity (centistokes) | 3.0 | 4.5 |
| Chemical Formula | $C_{16.17}H_{32.00}$ | $C_{15.26}H_{29.48}O_{1.70}$ |
| Carbon Fraction | 82 | 78 |
| Heating Values (kJ/kg) | 46,800 | 39,550 |

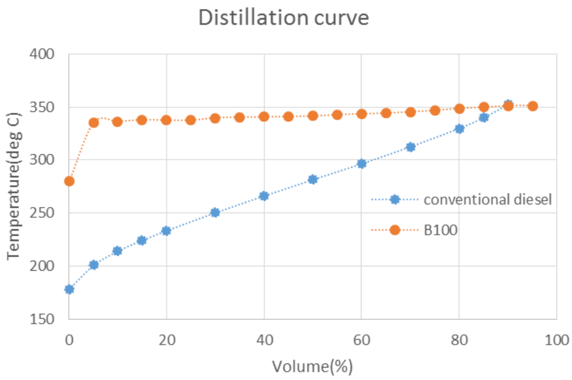


Fig. 1 Distillation curve of conventional diesel and biodiesel.

### 2.2 PM generator

PM was emitted from small CI engine. The engine has displacement of 638cm$^3$, compression ratio of 16.1:1 and power output of 8.8 kW. It is a naturally aspirated, single cylinder, four strokes, direct injection, and compression ignition engine. The fuel injection pressure was approximately 19.6 MPa. Fuel injection timing was constant timing at 19 degree BTDC.

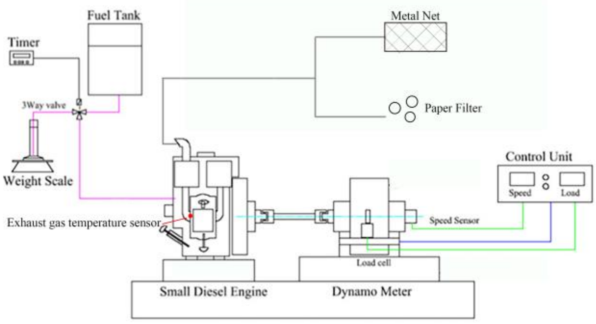


Fig. 2 Schematic diagram of tested small CI engine operation on dynamometer for particulate matter quantity measurement.

### 2.3 Method

The engine was connected to engine dynamometer to control engine load and engine speed. Fuel was supplied from fuel tank to weight scale using timer to control amount of fuel then weight scale measure fuel consumption which supplied to the engine in each condition. Exhaust gas temperature was measured 5cm after exhaust port. PM was trapped by metal net or paper filter depend on experiment as shown in "Fig. 2".

#### 2.3.1 Particle quantity

For PM quantity, The PM emitted from the engine was collected by opacity smoke meter (OKUDA DSM-240) filter paper. PM was collected approximately 20cm after exhaust valve in the same amount of suction period. Then PM quantity was measured by opacity smoke meter in five engine speed modes which consist of 1600, 1800, 2000, 2200 and 2400 rpm. At each engine speed, engine torque were varied with unload, 20%, 40%, 60% and 80% of maximum torque.

#### 2.3.2 Efficiency and particle size distribution

For particle size distribution analysis use laser diffraction technique using "MASTERSIZER 2000" machine. The particle was trapped by metal net after exhaust port around 50cm at 80% load and 2400rpm for every fuel.

#### 2.3.3 Morphology and nanostructures

Morphology and nanostructures of PM was investigated by using a scanning electron microscopy (SEM: EVO®MA10) and a transmission electron microscopy (TEM: JEOL JEM-2010).

## 3. Results and Discussions

### 3.1 PM quantity

"Fig. 3-Fig. 8" show smoke intensities of each fuel, engine load, and engine speed. Conventional diesel emitted the highest amount of smoke. The PM reduced by concentration of biodiesel due to oxygenate fuel. It was clearly observed that biodiesel engine's particulate matter was approximately a half of conventional diesel engine's particulate matter. When increase engine load, smoke intensity increased because more fuel was supplied to the engine. For engine speed it has a little different amount of smoke due to the engine efficiency of each engine speed. The lowest amount of smoke in each engine load usually occurs around 1800-2000rpm. When increase concentration of biodiesel, trend of engine speed which emitted lowest particulate matter(in the same load) shift to faster engine speed because bio diesel has a faster chemical reaction rate due to Biodiesel is oxygenate fuel which has oxygen in their molecule.

In addition, when operating at high engine speed, particulate matter was increase because of shorter oxidation time in combustion period.

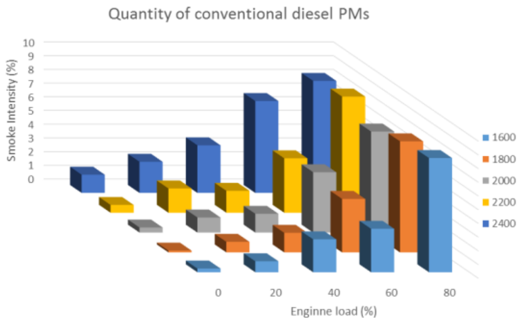


Fig. 3 Smoke intensity of conventional diesel

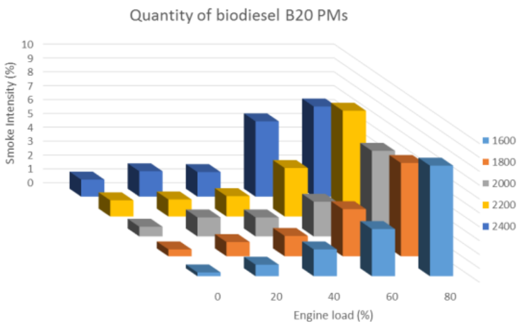


Fig. 4 Smoke intensity of B20

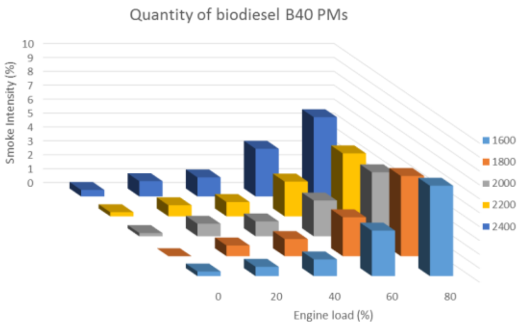


Fig. 5 Smoke intensity of B40

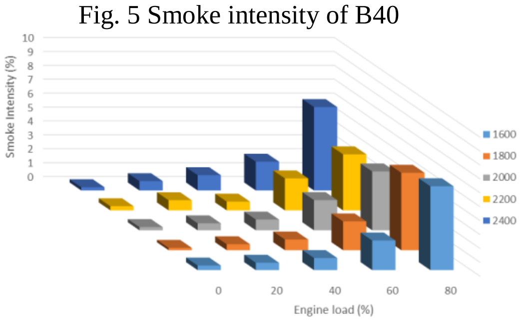


Fig. 6 Smoke intensity of B60

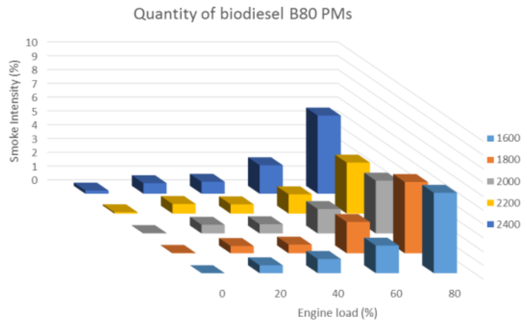


Fig. 7 Smoke intensity of B80

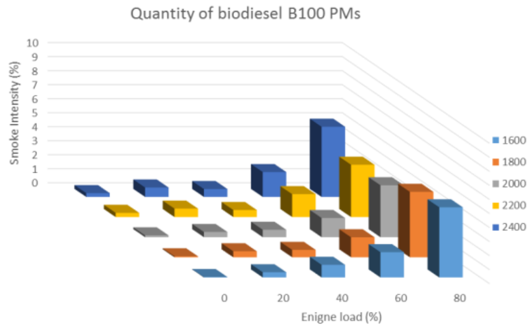


Fig. 8 Smoke intensity of B100

### 3.2 Efficiency and exhaust temperature

From the experiment result "Fig. 9" has shown when increase content of biodiesel, brake specific fuel consumption (BSFC) significantly increase around six percent. When engine dynamometer try to control the same power output of each fuel, biodiesel which has lower heating value have to inject more amount of fuel to compensate the lower energy output.

Although biodiesel has a worse brake specific fuel consumption but when consider on brake specific energy consumption (BSEC), trend is decrease inversely proportional with content of biodiesel. According to biodiesel is an oxygenate fuel which can combust more completely. So the thermal efficiency is increase and energy demand to create the power output is decrease.

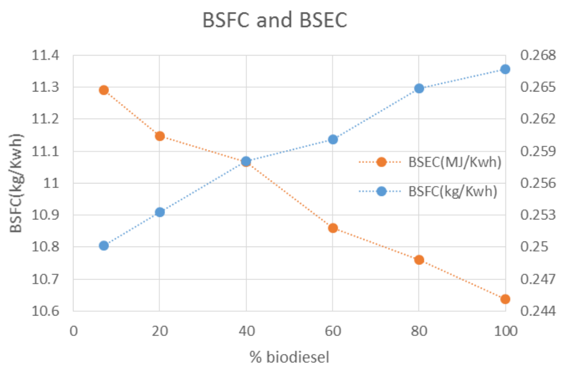


Fig. 9 Brake specific fuel consumption and brake specific energy consumption at 80% load and 2400rpm on each fuel

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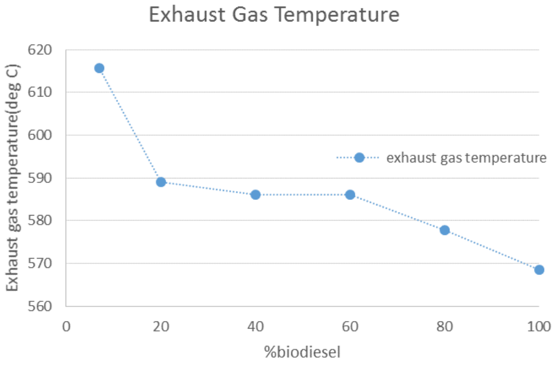


Fig. 10 Exhaust gas temperature at 80% load and 2400rpm on each fuel

Trend of exhaust gas temperature “Fig. 10” is inversely proportional with biodiesel fraction. Due to two reason, first is distillation curve in “
” which biodiesel start to change their phase from liquid to gas phase at higher temperature than conventional diesel. And mass of biodiesel which use for combustion per cycle is more than conventional diesel from BSFC in “Fig. 9”. It mean in the combustion reaction biodiesel have to absorb much more energy than conventional diesel to change their phase before combustion process. And the second reason is Biodiesel has higher cetane number thus the advance combustion (premixed combustion phase) should be found lead to the shorter combustion duration lead to the lower temperature with biodiesel fuel blends. From those reason, the higher content of biodiesel, the lower exhaust gas temperature.

### 3.3 Particle size distribution

Particle which emitted from internal combustion engine clearly separate into 3 modes [18].

First is nucleation mode, but the nuclei particles are too small for the particle size distribution measure instrument.

Second is accumulation mode which shown in first peak of “Fig. 11”. The size range of agglomerate is ~40-400nm, average size is ~130-142nm, and mode size is ~100-120nm. When compare the average size of particles form laser diffraction technique with image processing technique [19] which the average size of diesel particulate matter is 131nm and biodiesel is 134nm. That result can be confirm that these two methods of measuring get the similar result which have different <10%. The higher content of oxygen in fuel, the higher amount and smaller size of agglomerate because of more complete combustion. Which can see in better BSEC.

Third is coarse mode such as PM2.5 and PM10 which shown in second peak of the “Fig. 11”. The higher content of conventional diesel, the higher amount of particle in coarse mode.

The result of particle size distribution in every fuel show the similar trend of particle mode separation. The size of each modes are similar but the amount is different by the fraction of biodiesel.

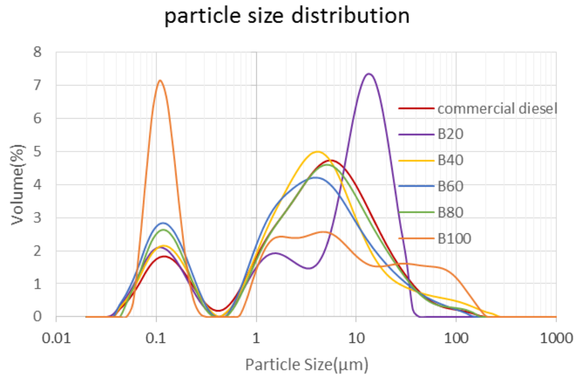


Fig. 11 particle size distribution at 80% load 2400 rpm of each fuel

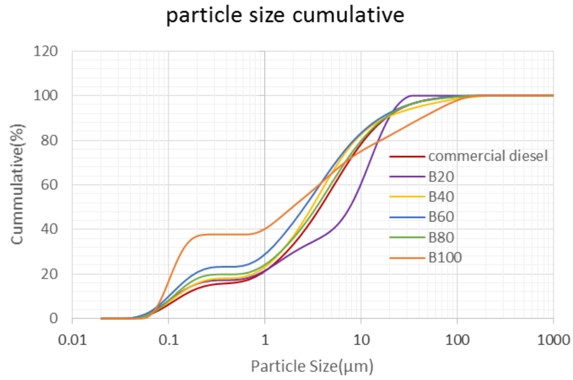


Fig. 12 particle size cumulative at 80% load 2400 rpm of each fuel

### 3.4 Morphology and nanostructures

The morphology of engine’s particulate matter was successfully investigated using electron microscopy. Several type of PM spread all of the filters for example PM10 which have size around 10 micron, PM2.5 or fine particle, ultrafine particle and nanoparticle were clearly seen using SEM and TEM. “Fig. 13” shows SEM image of PM10 from biodiesel engine in the condition of 80% load engine operation. In “Fig. 14 and Fig. 15” shows PM2.5 from the same condition with “Fig. 13”.

Both of PM10 and PM2.5 of diesel and biodiesel engine’s particulate matter consist of many single nanoparticles.

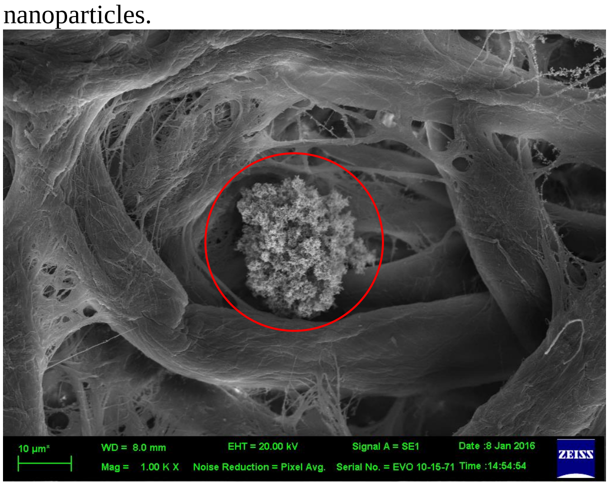


Fig. 13 SEM image of biodiesel blends diesel engine’s PM10 in the condition of 80% load engine operation.

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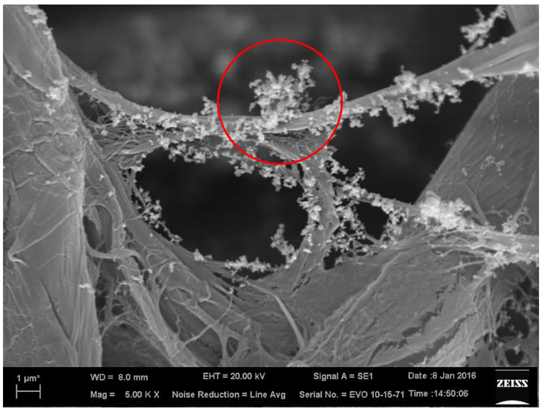


Fig. 14 SEM image of conventional diesel particulate matter in condition of 80% load operation

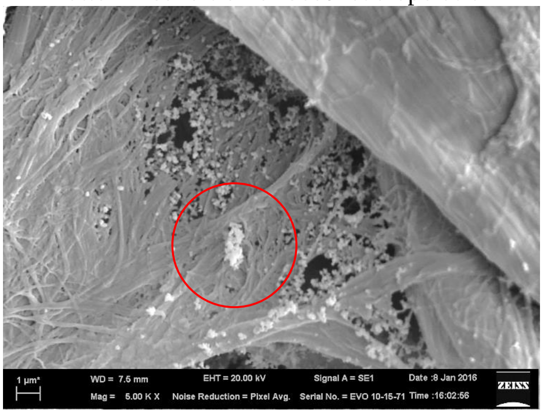


Fig. 15 SEM image of biodiesel particulate matter in condition of 80% load operation

In addition, ultrafine particles and nanostructure of PM single particle were investigated using TEM for better understanding. "Fig. 16 and Fig. 17" shows TEM images of diesel and biodiesel engine's particulate matter ultrafine particles, respectively, in the condition of 80% load engine operation. The average agglomerated particle diameter size are in the range of 40-400nm.

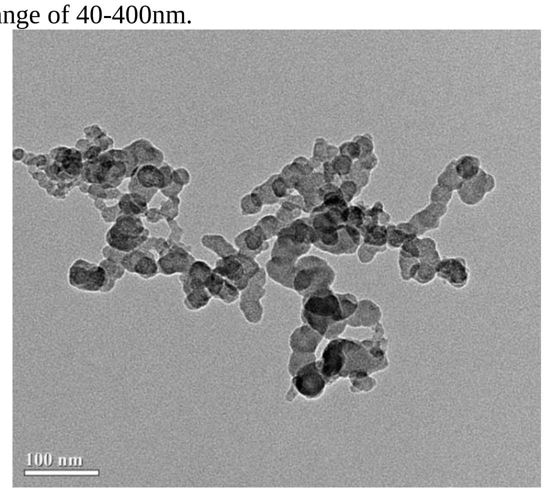


Fig. 16 TEM image of conventional diesel particulate matter ultrafine particles in the condition of 80% load operation

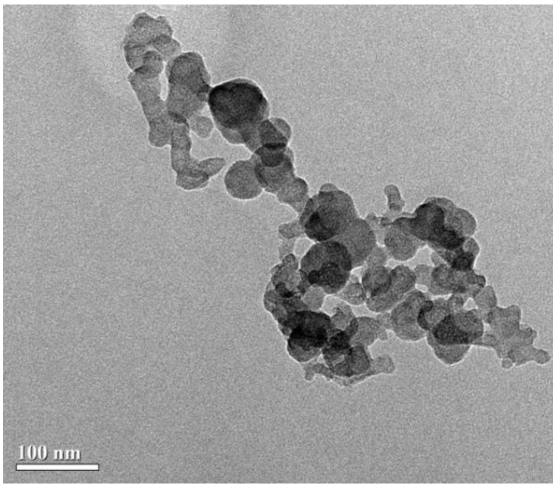


Fig. 17 TEM image of biodiesel particulate matter ultrafine particles in the condition of 80% load operation

Moreover, single nanoparticles of diesel and biodiesel engines was also clearly observed using TEM as shown in "Fig. 18 and Fig. 19", respectively. The average agglomerated particle diameter size are in the range of 20-50nm. Each carbon platelet, inner core and outer shell of single nanoparticle was also clearly observed by TEM.

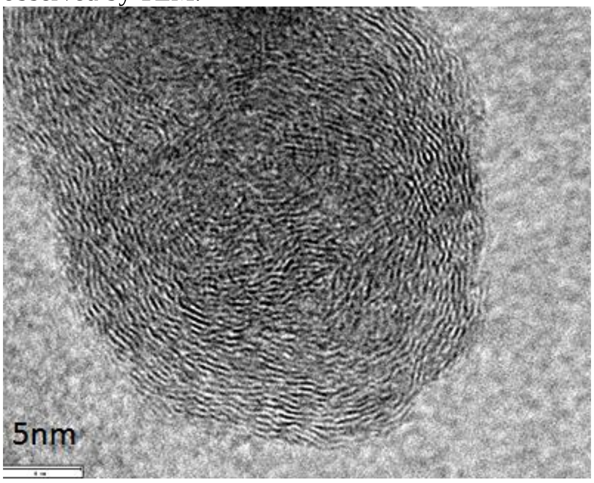


Fig. 18 TEM image of conventional diesel nanoparticle in condition 80% load operation

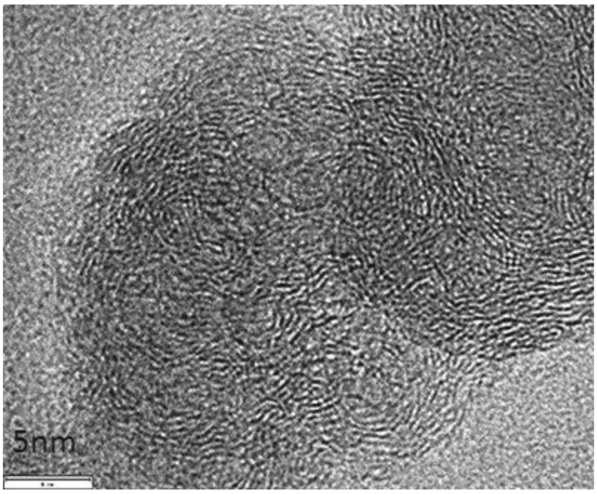


Fig. 19 TEM image of biodiesel nanoparticle in condition 80% load operation

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## 4. Conclusion

The amount of particulate matter (PM) emitted from CI engine depend on several variables. The result shows the parameter which has the highest effect on smoke intensity or PM quantity is engine load, concentration of biodiesel and engine speed respectively. When increase concentration of biodiesel in fuel, PM reduce because oxygen concentration in fuel increase. Higher concentration of oxygen makes more complete combustion, better BSEC, smaller particle, and lower exhaust temperature. The quantities of particulate matter emitted from biodiesel engine are approximately a half of diesel engine's particulate matter. Morphology of CI engine's PM10, PM2.5, ultrafine particle and nanoparticle was characterized using SEM and TEM successfully. The morphology of biodiesel and conventional diesel doesn't have significant different on every type of particle. Average single nanoparticle sizes of diesel and biodiesel engine's particulate matter is approximately 20-50 nm. Average agglomerate size of diesel and biodiesel engine's particulate matter is ~130-142nm similar to the image processing result from TEM image in the previous research [19].

Smaller particulate matter from biodiesel fuel should be consider to design and development of Diesel Particulate Filter (DPF) configuration for biodiesel blends diesel CI engines in the future.

## 5. Acknowledgement

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