

สำนักหอสมุดกลาง พระจอมเกล้าลาดกระบัง

**THE IMPACT OF BIODIESEL PARTICULATE MATTER
MORPHOLOGY AND OXIDATION KINETIC ON FILTER
TRAPPING AND REGENERATION MECHANISM**



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Thesis	The Impact of Biodiesel Particulate Matter Morphology and Oxidation Kinetic on Filter Trapping and Regeneration Mechanism
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ABSTRACT

As well-known, the diesel engine has the highest thermal efficiency at the same load as compared with other internal combustion engine but its disadvantage is particulate matter (PM) emitted to the atmosphere. Because the particulate matter can effect to human health so it has to remove from the exhaust gas before emitted to the atmosphere. The studies of this research were divided in to two parts. The first part studied about physical and chemical characteristic of diesel and biodiesel particulate matter by using scanning electron microscope (SEM), transmission electron microscope (TEM) and thermo-gravimetric analysis (TGA). The second part studied the trapping of particulate matter on conventional diesel particulate (DPF) filter mechanism and regeneration of particulate filter mechanism with the testing equipment. The result of this research can be good information of diesel and biodiesel particulate matter characteristic in Thailand and also can be used for the development of advanced academic and the practical in industry.

Keywords: Diesel engine, Particulate matter, Biodiesel fuel, Diesel particulate filter

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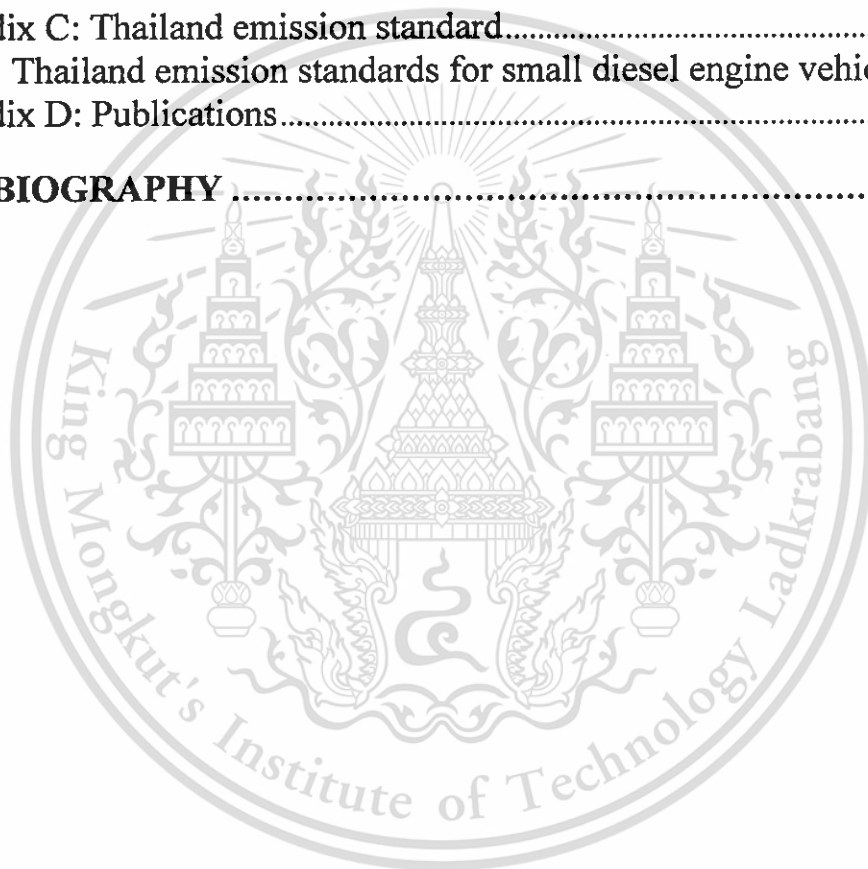
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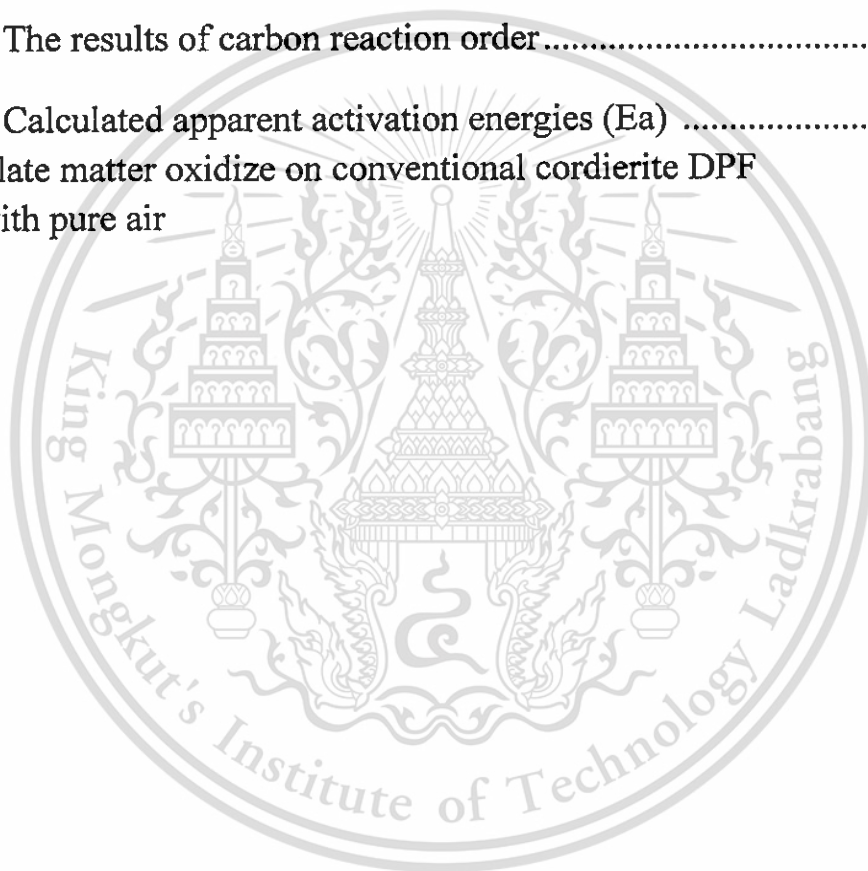
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Chapter 1

INTRODUCTION

1.1 Background

Nowadays, the shortage of energy is the one of main problem in the world. The global energy demand, reported by International Energy Agency, has been increasing continuously. The energy demand to year 2030 of transportation sector is glowing approximately 1.7% per year as shown in Fig. 1.1 and the energy from oil is 36 % of global energy using which the biggest factor as shown in figure 1.2. Thus, the finding for using worthy or renewable energy is the way to solve this crisis. One of this is the using of high efficiency engine. As a well-known that a diesel engine has the highest thermal efficiency, where is more than 30% thermal efficiency, when compare with other internal combustion engine at the same load. The increasing number of diesel engine is an alternative to increase the efficiency of liquid fuel which limited in the world. However, the main pollutants from diesel engine are solid particles (Particulate Matter: PM) and nitrogen oxide (NOx) [1]. The pollutants should be removed from exhaust gas because of their effects on environment and human health, such as lung cancer. Hence, the regulation of pollution standard for diesel emission is proper way to control the emission that emitted to the atmosphere.

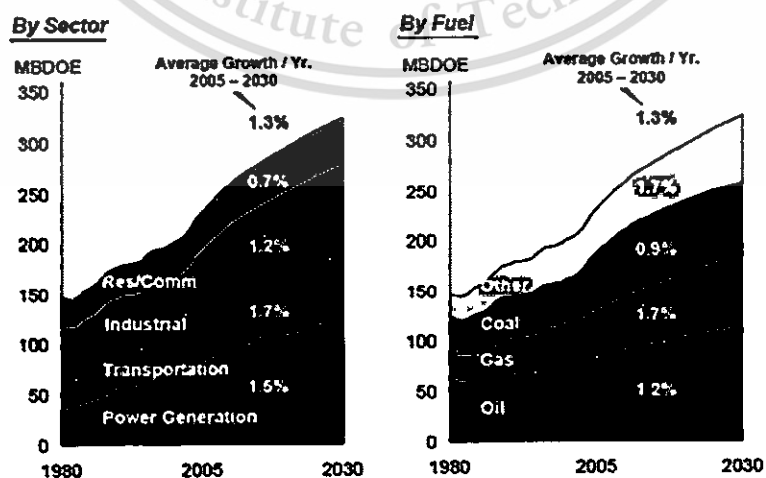


Figure 1.1 Global energy demands, View to the year 2030 [2]

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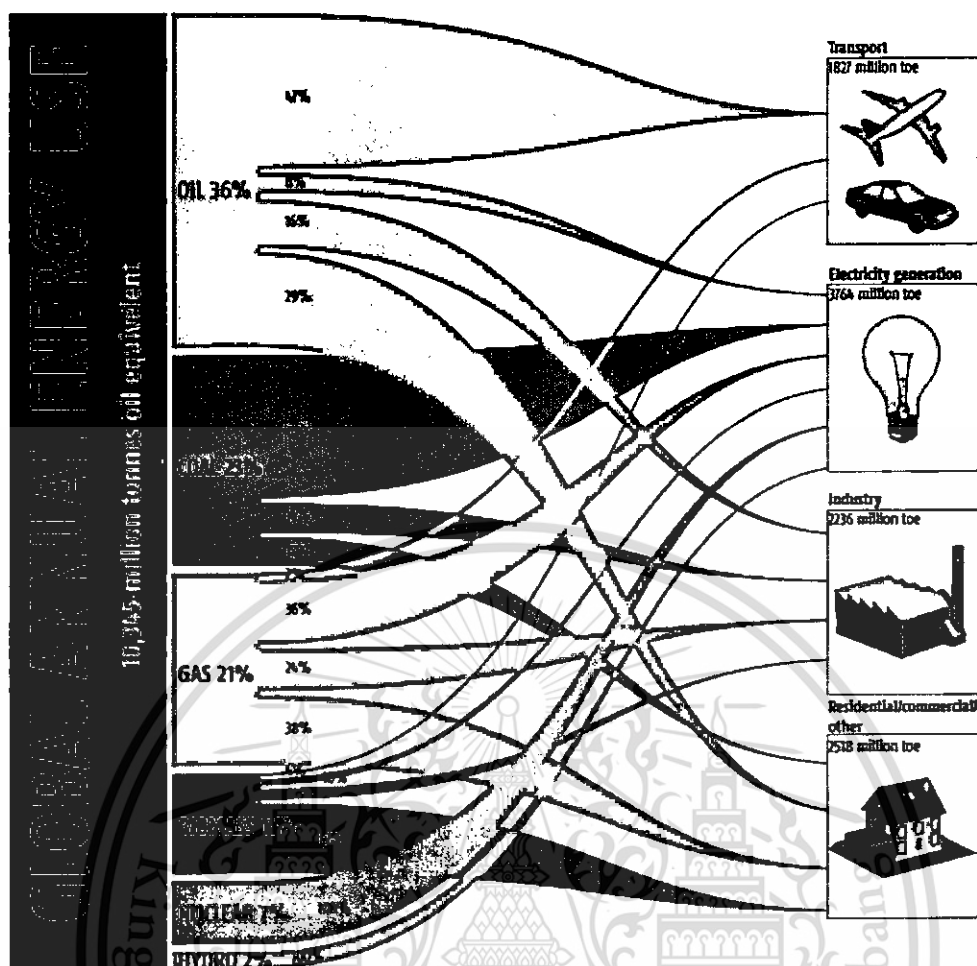


Figure 1.2 World energy use and the sectorial split of fuel use [3]

In 1 January 2012, the government of Thailand regulates to use the standard level 7 or Euro 4 to control the emission which release from diesel engine by the particulate matter must be not over 0.025 g/km and nitrogen oxide must be not over 0.25 g/km.

The biofuel such as biodiesel diesel is the good option to substitute for fossil fuel. Because biofuel can be made from biomass and can re-produce faster than fossil fuel. Therefore, Thailand government promotes the using of biodiesel to Thai people. Due to, biodiesel can be produced in country with the domestic agriculture product of plam oil, jatropha oil, and etc. The advantage of biodiesel is low sulfur and aromatic hydrocarbon content. Beside, biodiesel has oxygen atom in fuel molecule and also acts like environmental friendly fuel. Even if, the combustion of biodiesel fuel emits greenhouse gas (CO_2) to atmosphere as same as diesel fuel but in theoretical the biodiesel fuel can substantial reduce the net greenhouse gas. Due to, the biodiesel was made from biomass, as plants which the growth of plants pulls out the carbon dioxide gas from atmosphere by photosynthesis. So the

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carbon dioxide gas was emitted from biofuel' s combustion and the carbon dioxide absorption by plants is balance, the increasing of greenhouse gas in the atmosphere can assume to be zero. Furthermore, the bio – oxygenated fuel also promote more completely combustion than fossil fuel that mean it emit low amount of particulate matter.

However, the particulate matters from diesel and biodiesel combustion have to remove from exhaust gas before emit to the atmosphere. The after treatment technology is appropriate to use in particulate emission reduction. Diesel particulate filter is new technology for particulate matter removing application. Diesel particulate filter has two main types presently use. Full flow filter is high trapping efficiency, 90% removing by mass and 99% removing by number. Second one, the partial flow filter collects some particulate matter out of engine while the residue is flow through to the air. The trapping efficiency of the partial flow is approximately 50%.

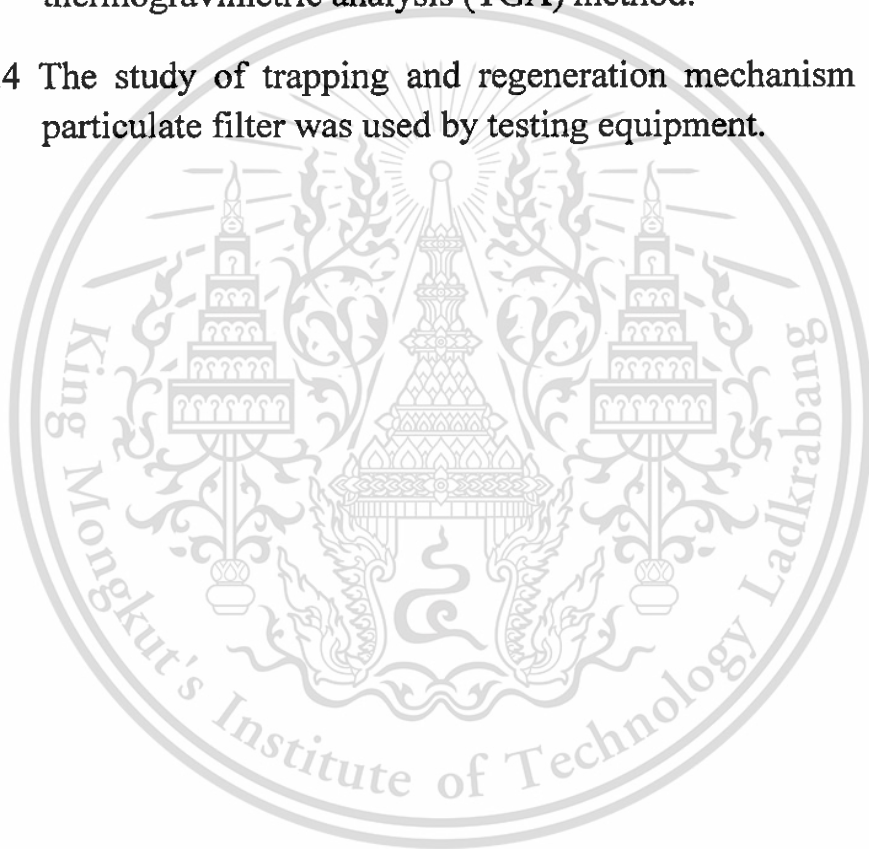
In this research, particulate matter from diesel and biodiesel was investigated about physical and chemical characteristic such as quantity, particle size in sing and agglomerate, oxidation kinetic. Eventually, the particulate matter was also investigated in trapping and regeneration mechanism on diesel particulate filter with small diesel engine.

1.2 Objectives

- 1.2.1 To investigate and analyze the physical characteristic of diesel and biodiesel particulate matter.
- 1.2.2 To investigate and analyze the chemical characteristic of diesel and biodiesel particulate matter.
- 1.2.3 To study the effect of diesel and biodiesel particulate matter trapping mechanism and diesel particulate filter regeneration mechanism.

1.3 Scope of work

- 1.3.1 The investigation of particulate matter concentration and quantities was used by smoke meter and air filter.
- 1.3.2 The analysis of particulate matter morphology in single and agglomerate size was used the image processing method by measuring from transmission electron microscope (TEM) and scanning electron microscope (SEM) image.
- 1.3.3 The analysis of particulate matter oxidation kinetic was used by thermogravimetric analysis (TGA) method.
- 1.3.4 The study of trapping and regeneration mechanism of diesel particulate filter was used by testing equipment.



Chapter 2

RESEARCH THEORY

2.1 Diesel engine

A conventional internal combustion diesel engine works on “Diesel Cycle”. In the simple diesel engines, an injector injects diesel into the combustion chamber above the piston directly. Diesel engines are also commonly known as Compression-Ignition engines; since the diesel is burned due to hot compressed air. The temperature of the air inside the combustion chamber rises to above 400°C to 800°C, which in turn, ignites the diesel which was injected into the combustion chamber. The ‘Diesel Cycle’ does not use an external mechanism such as a spark-plug to ignite the air-fuel mixture. The principle of diesel cycle can be divided into 4 strokes, as shown in figure 2.1.

1. Suction – With pistons moving downwards and opening of the inlet valve creates suction of clean air into the cylinders.
2. Compression – With closing of Inlet valve the area above the piston gets closed. The piston moves up resulting in compression of the air in a confined space under higher compression-ratio.
3. Combustion – At this stage the injector sprays the diesel into the combustion chamber. The rise in temperature of the air caused by its compression; results in instantaneous burning of diesel with in an explosion. This causes heat to release resulting in generation of expanding forces known as power. These forces again push the pistons downwards resulting in their reciprocating motion.
4. Exhaust– On their way up, the pistons push the exhaust gases above them thru’ the exhaust valve which opens during exhaust stroke.

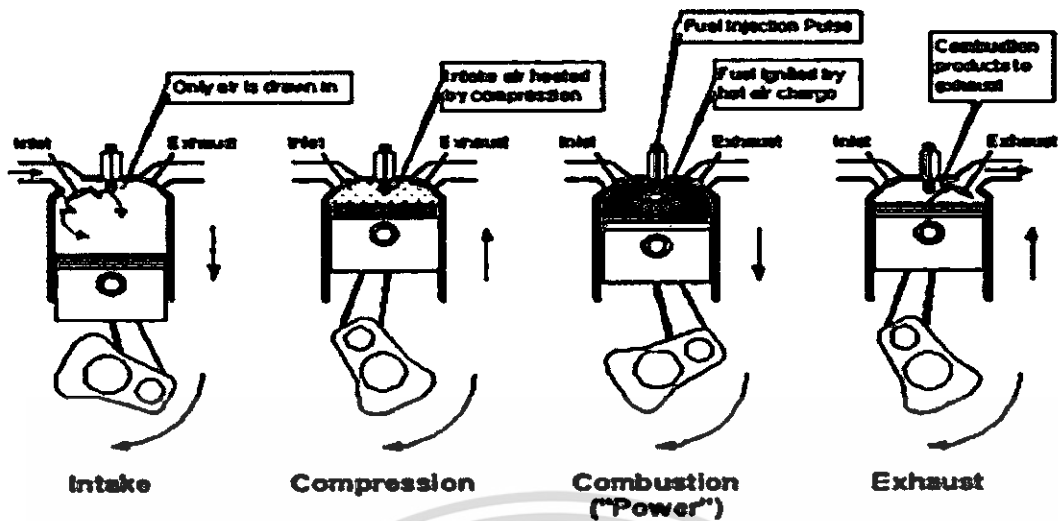


Figure 2.1 Diesel cycle [4]

The heat release rate (figure 2.2) in combustion stroke of diesel cycle has 4 stage which consist of ignition delay phase, premixed combustion phase, mixing-controlled combustion phase and late combustion phase. The heat release rate explain the process as

- Ignition Delay Phase, a - b is the time period since the start of fuel injection in the combustion chamber until the fuel ignited.
- Premixed Combustion Phase, b - c is the time duration of the premixed fuel combustion after ignition delay phase which will initiate the rapid auto - ignition and increase heat release rate.
- Diesel Fuel Performance Mixing Combustion Phase, c - d is occurred in combustion chamber after the completely burned of premixed fuel. The combustion rate will be controlled by the formation rate of mixture between air - fuel that ready to be burned.
- Late Combustion Phase, d - e is the period that the heat release rate is low during the exhaust stroke. It is the combustion of the rest of the fuel and carbon residue which previously generated from the rich mixture.

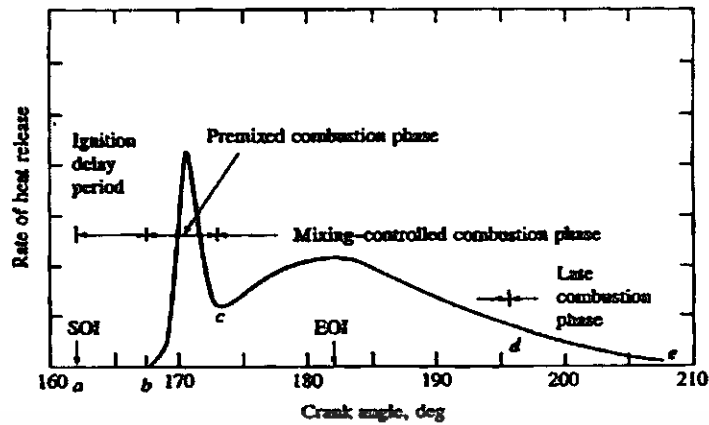


Figure 2.2 Stage of heat release rate [5]

2.2 Emission of diesel engine

Diesel engines convert the chemical energy contained in the fuel into mechanical power. Diesel fuel is injected under pressure into the engine cylinder where it mixes with air and where the combustion occurs. The exhaust gases which are discharged from the engine contain several constituents that are harmful to human health and to the environment. By the emission of diesel engine consist of CO, HC, NO_x, SO₂ and particulate matter as shown on eq.2.1 and figure 2.3 shown the combustion phenomena in combustion chamber.

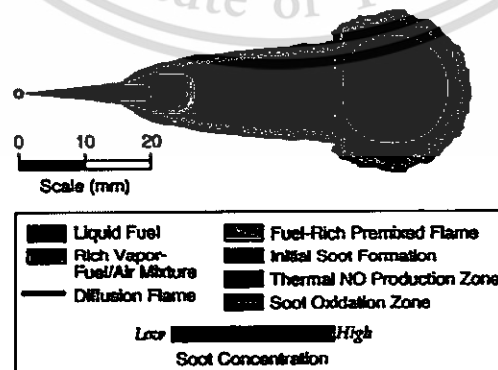


Figure 2.3 Diesel combustion flame zone [6]

Carbon monoxide (CO), hydrocarbons (HC), and aldehydes are generated in the exhaust as the result of incomplete combustion of fuel. A significant portion of exhaust hydrocarbons is also derived from the engine lube oil. When engines operate in enclosed spaces, such as underground mines, buildings under construction, tunnels or warehouses, carbon monoxide can accumulate in the ambient atmosphere and cause headaches, dizziness and lethargy. Under the same conditions, hydrocarbons and aldehydes cause eye irritation and choking sensations. Hydrocarbons and aldehydes are major contributors to the characteristic diesel smell. Hydrocarbons also have a negative environmental effect, being an important component of smog.

Nitrogen oxides (NO_x) are generated from nitrogen and oxygen under the high pressure and temperature conditions in the engine cylinder. NO_x consist mostly of nitric oxide (NO) and a small fraction of nitrogen dioxide (NO_2). Nitrogen dioxide is very toxic. NO_x emissions are also a serious environmental concern because of their role in the smog formation.

Sulfur dioxide (SO_2) is generated from the sulfur present in diesel fuel. The concentration of SO_2 in the exhaust gas depends on the sulfur content of the fuel. Low sulfur fuels of less than 0.05% sulfur are being introduced for most diesel engine applications. Sulfur dioxide is a colorless toxic gas with a characteristic, irritating odor. Oxidation of sulfur dioxide produces sulfur trioxide which is the precursor of sulfuric acid which, in turn, is responsible for the sulfate particulate matter emissions. Sulfur oxides have a profound impact on environment being the major cause of acid rains.

Particulate matter (PM) is a complex aggregate of solid and liquid material. Its origin is carbonaceous particles generated in the engine cylinder during combustion. The primary carbon particles form larger agglomerates and combine with several other, both organic and inorganic, components of diesel exhaust.

2.3 Particulate matter

Particulate matter is the most characteristic of diesel emissions which responsible for the black smoke traditionally associated with diesel powered vehicles. The diesel particulate matter emission is usually abbreviated as PM or DPM. Particulate matter was divided into three characteristic ranges of size: nucleation mode, accumulation mode and coarse mode. The nucleation-mode particles are more arcane: most are probably formed from nucleated volatiles, Accumulation mode particles are constructed from a solid core of carbonaceous building blocks called 'spherules', together forming 'agglomerates' within the range of 60–100 nm. Spherules are fairly uniform in size, i.e. mostly 20–50 nm. The coarse-mode particles are solid and are formed from the other two modes through a process of storage and release in the exhaust system, or through material disintegration. Composition-wise, there are five distinct 'fractions': ash, carbonaceous, organic, sulphate and nitrate as shown figure 2.4. The diesel particulate matter has a complicated physical and chemical structure.

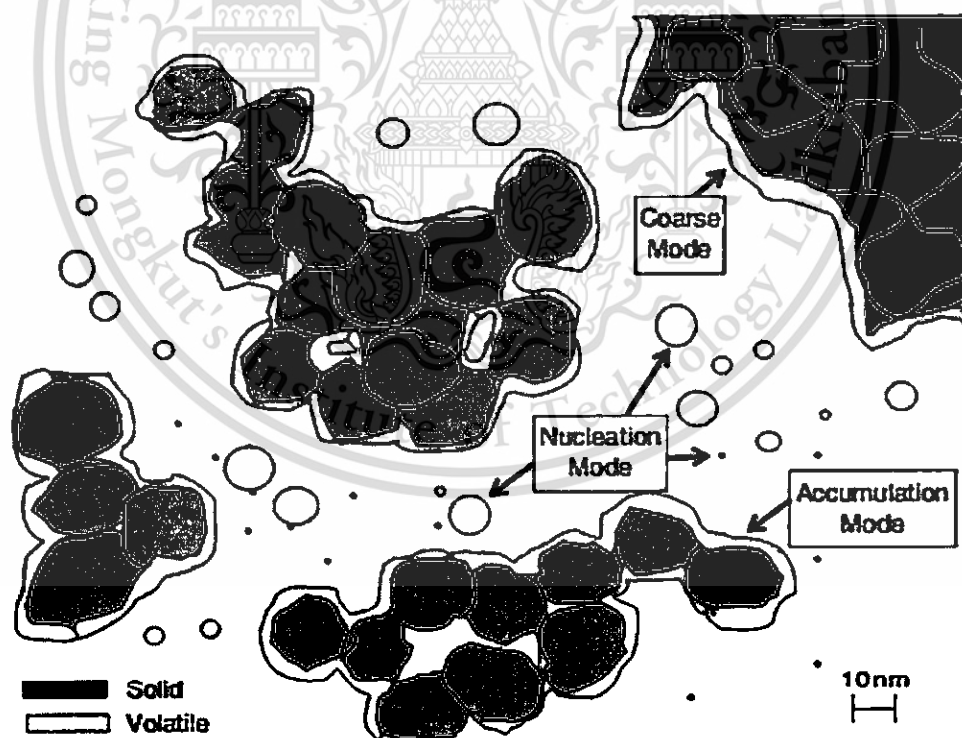


Figure 2.4 Depicted schematically of particulate matter: coarse mode (largest, shown in part), nucleation mode (smallest); accumulation mode (midding) [7]

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Two main elements of diesel particulate matter are Solid Organic Fraction (SOL), consisting of carbon and metallic ash, and the Soluble Organic Fraction (SOF), consisting of hydrocarbon. Figure 2.5 is also illustrated the definition of size of atmosphere particles: PM10, D (diameter) $< 10 \mu\text{m}$; fine particles, $D < 2.5 \mu\text{m}$; ultrafine particles, $D < 0.10 \mu\text{m}$; and nano - particles, $D < 0.05 \mu\text{m}$ or 50 nm.

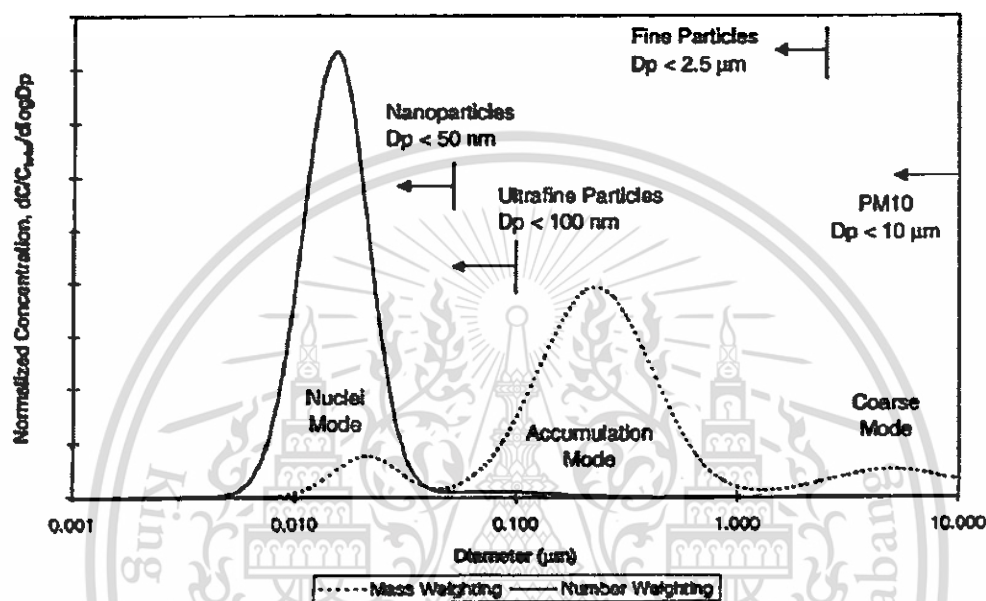


Figure 2.5 Particle size distribution of soot from a diesel engine [8]

2.4 Diesel Particulate filter

Diesel particulate filters (DPF) are devices that physically capture diesel particulates to prevent their release to the atmosphere. Diesel particulate filter materials have been developed that show impressive filtration efficiencies, in excess of 90%, as well as good mechanical and thermal durability. Diesel particulate filters have become the most effective technology for the control of diesel particulate emissions, including particle mass and numbers with high efficiencies. Due to the particle deposition mechanisms in these devices, filters are most effective in controlling the solid fraction of diesel particulates, including elemental carbon (soot) and the related black smoke emission. Filters may have limited effectiveness, or be totally ineffective, in controlling non-solid fractions of PM emissions (SOF and sulphate particulates). To control total PM emissions, DPF

systems are likely to incorporate additional functional components targeting the SOF typically oxidation catalysts while ultra-low sulfur fuels may be required to control sulfate particulates. The majority of particulate filters work by filtering the soot particles (i.e., storing the soot in the filter) until a prescribed level of flow resistance is detected, at which point a regeneration process is initiated as shown in figure 2.6. A wall flow filter is generally made of ceramic materials, such as cordierite or silicon carbide (SiC), and consists of several rectangular channels with alternate channels blocked with cement at each end. The exhaust gas is forced to flow through a channel wall having numerous micron-scale pores. Particulate matter is filtered from the exhaust gas by the micro-scales pores while the exhaust gases flow through the wall, as shown in figure 2.7.

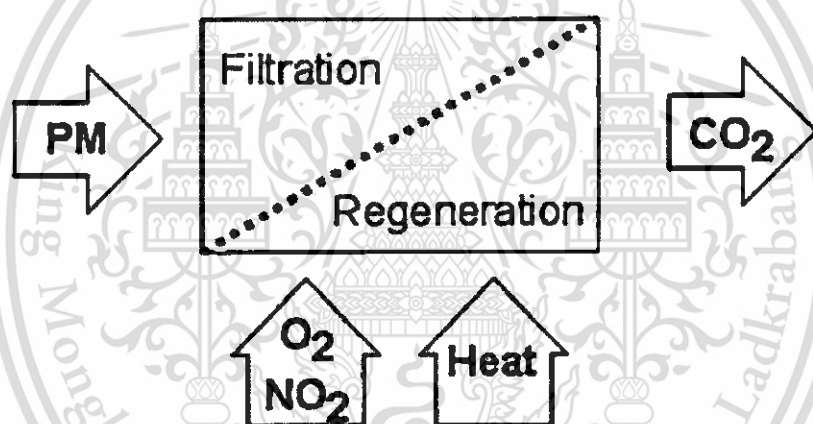


Figure 2.6 Schematic of Particulate Filter with Thermal Regeneration [9]

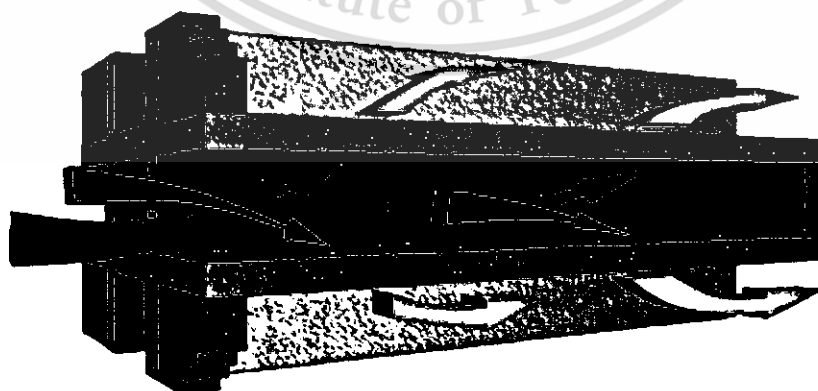


Figure 2.7 Schematic of gas flow through DPF [10]

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In order to provide a suitable condition for oxidation, the enough temperature and oxidative materials such as oxygen or nitrogen dioxide (or its precursors) are required. In passive regeneration, the heat source is the engine exhaust temperature and the filter is regenerated continuously during engine working time. Application of catalyst in filters, in order to decrease the oxidation temperature of trapped soot, is prevalent. In Active form of regeneration of DPF, the filter is dismantled from the system periodically and is heated up in order to burn the trapped particles.

2.5 Characterization of particulate trapping

The general trapping concept of the particulate matter inside the diesel particulate filter was divided into 4 stages as shown in figure 2.8. Initially, the clean particulate filter is shown in stage 1. Stage 2 shows the particulate matters is collecting on the substrate pores inside the filter wall. Stage 3 shows the bridging of the filter pore. In this stage, the particulate matter from the engine combustion accumulates on the pore structure inside the filter wall until the pore is blocked. Finally, stage 4, the particulate matter develops and glows as the thin cake layer on the inlet channel wall [11].

A conceptual model of the pressure drop in trapping process was shown in figure 2.9. The pressure drop rises quickly as the pores become plugged in stages 1 to 3 figure 2.8. As seen figure 2.9, transitioning from stage 1 to 2 has less effect on the pressure drop than the transition from stage 2 to 3. The figure also shows that the pressure drop during stages 1 to 3 increases non-linearly, but, once stage 4 is reached, there is a linear and slower rise in the pressure drop curve as the cake layer thickens.

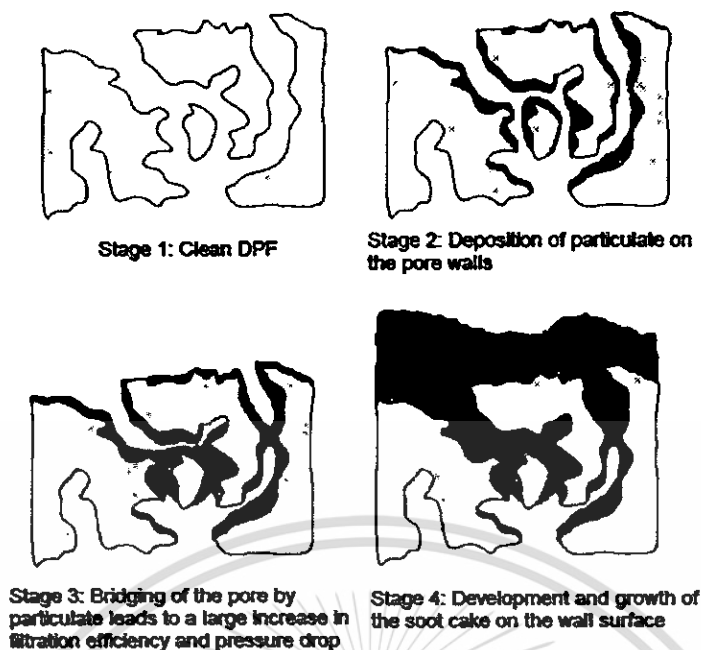


Figure 2.8 Conceptual model of PM trapping on the DPF wall [11]

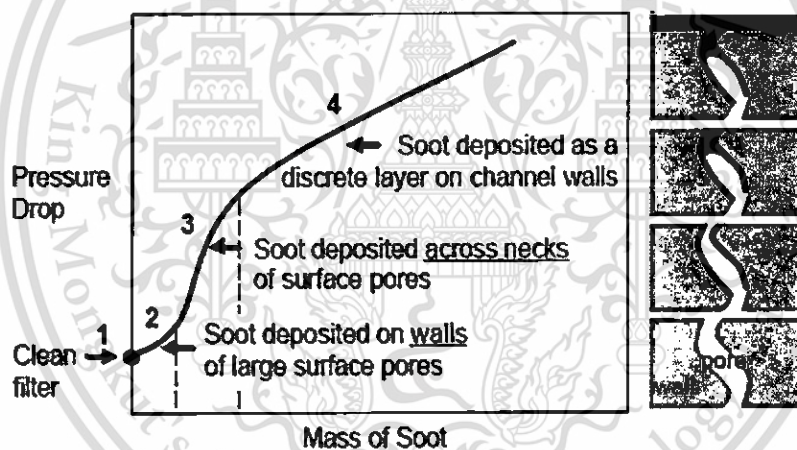


Figure 2.9 Conceptual model of pressure drop during particulate trapping [12]

2.6 Alternative fuel: Biodiesel

Renewable bio-oxygenated fuels – liquid and gaseous fuels derived from organic matter – can play an important role in reducing CO₂ emissions (greenhouse gas effect and global warming) because of bio-fuels is the carbon neutral, as shown in figure 2.10.

To reduce dependency on oil and to contribute to growing efforts to decarbonize the transport sector, bio-fuels release shifting to low-carbon, non-petroleum fuels, often with minimal changes to vehicle stocks and

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distribution infrastructure. While improving vehicle efficiency is by far the most important low-cost way of reducing CO₂ emissions in the transport sector, bio-fuels will need to play a significant role in replacing liquid fossil fuels suitable for planes, marine vessels and other heavy transport modes that cannot be electrified. Production and use of bio-fuel can also provide benefits such as increased energy security, by reducing dependency on oil imports, and reducing oil price volatility. In addition, bio-fuels can support economic development by creating new sources of income in rural areas, as shown in figure 2.11.

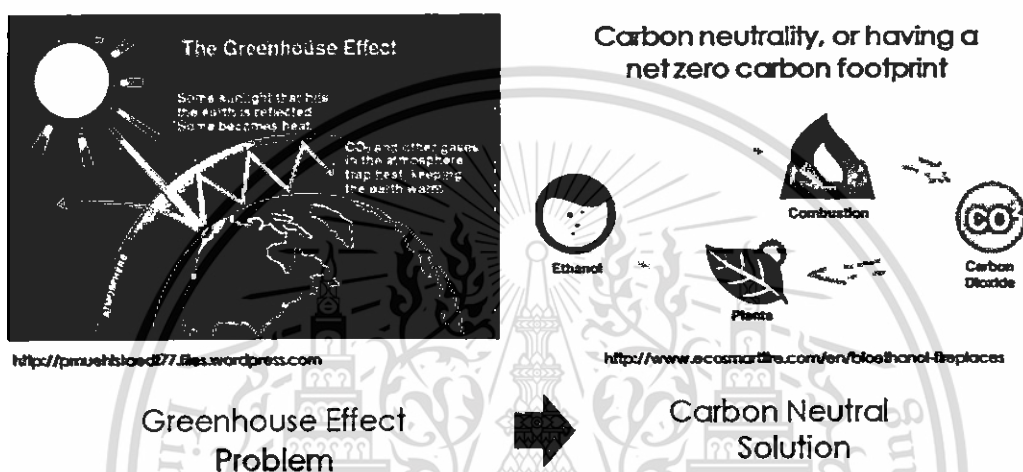


Figure 2.10 The greenhouse effect (Carbon dioxide) and the concept of carbon neutral of renewable bio-oxygenated fuels

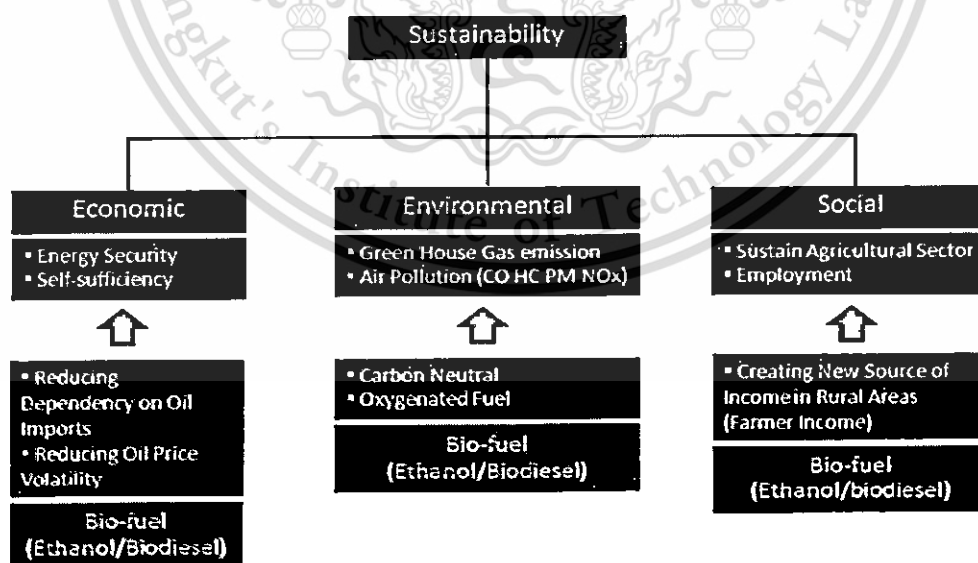


Figure 2.11 Summary of influence of renewable bio-oxygenated fuel (Ethanol and Biodiesel) for economic, environmental and social

Biodiesel is an alternative fuel for diesel engines that is produced by chemically reacting a vegetable oil or animal fat with an alcohol such as methanol. The reaction requires a catalyst, usually a strong base, such as sodium or potassium hydroxide, and produces new chemical compounds called methyl esters. It is these esters that have come to be known as biodiesel. Because its primary feedstock is a vegetable oil or animal fat, biodiesel is generally considered to be renewable. Since the carbon in the oil or fat originated mostly from carbon dioxide in the air, biodiesel is considered to contribute much less to global warming than fossil fuels. Diesel engines operated on biodiesel have lower emissions of carbon monoxide, unburned hydrocarbons, particulate matter, and air toxics than when operated on petroleum-based diesel fuel. Biodiesel is produced through a process known as transesterification, as shown in figure 2.12. By R₁, R₂, and R₃ are long hydrocarbon chains, sometimes called fatty acid chains. There are only five chains that are most common in soybean oil and animal fats (others are present in small amounts) [13].

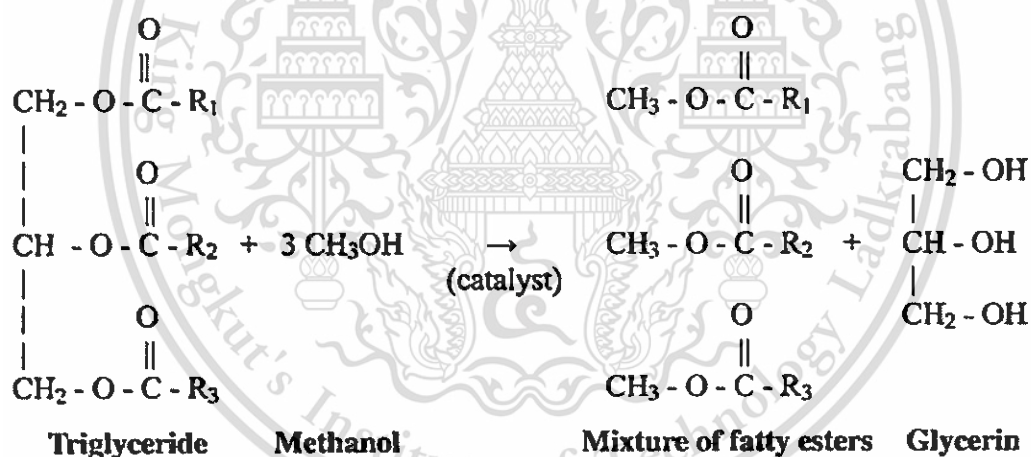


Figure 2.12 Transesterification of Vegetable Oil to Biodiesel [13]

2.7 Technical analysis

2.7.1 Scanning electron microscope

The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample. In most applications, data are collected over a selected area of the surface of the sample, and a 2-dimensional image is generated that displays spatial variations in these properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnification ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm). The main SEM components include: Source of electrons, Column down which electrons travel with electromagnetic lenses, Electron detector, Sample chamber and Computer and display to view the images as shown in figure 2.13. Electrons are produced at the top of the column, accelerated down and passed through a combination of lenses and apertures to produce a focused beam of electrons which hits the surface of the sample. The sample is mounted on a stage in the chamber area and, unless the microscope is designed to operate at low vacuums, both the column and the chamber are evacuated by a combination of pumps. The level of the vacuum will depend on the design of the microscope. The position of the electron beam on the sample is controlled by scan coils situated above the objective lens. These coils allow the beam to be scanned over the surface of the sample. This beam scanning, as the name of the microscope suggests, enables information about a defined area on the sample to be collected. As a result of the electron-sample interaction, a number of signals are produced. These signals are then detected by appropriate detectors.

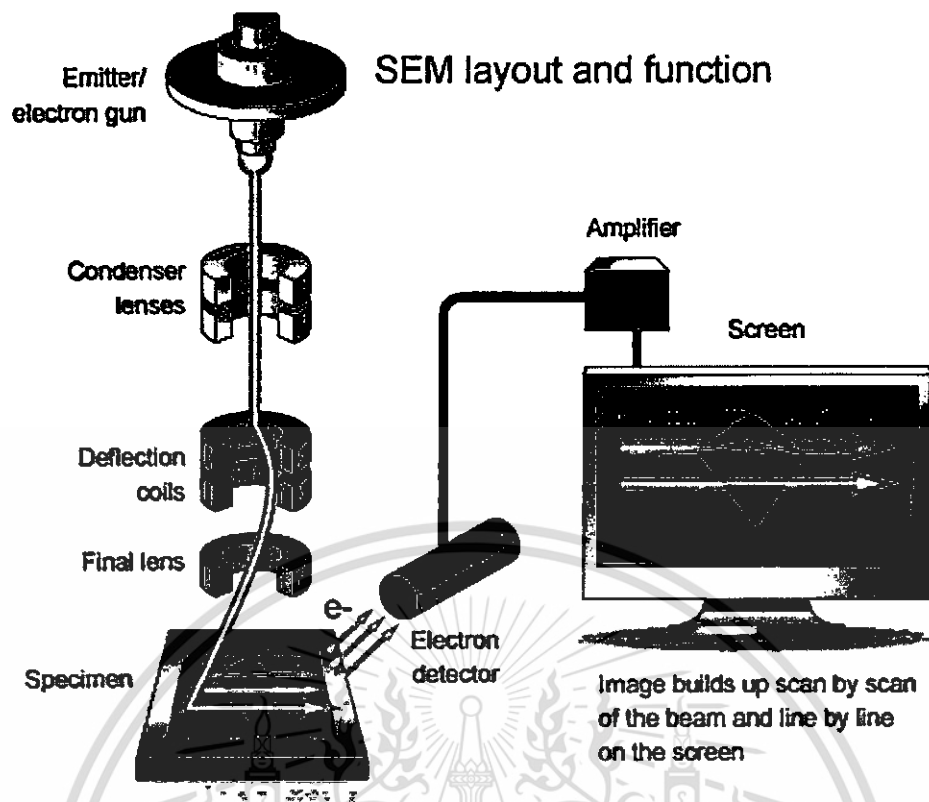


Figure 2.13 Schematics of scanning electron microscopy operation [14]

2.7.2 Transmission electron microscope

The transmission electron microscope (TEM) is a very powerful tool for material science. A figure 2.14 shown schematic of transmission electron microscopy operation by a high energy beam of electrons is shone through a very thin sample, and the interactions between the electrons and the atoms can be used to observe features such as the crystal structure and features in the structure like dislocations and grain boundaries. Chemical analysis can also be performed. TEM can be used to study the growth of layers, their composition and defects in semiconductors. High resolution can be used to analyze the quality, shape, size and density of quantum wells, wires and dots. The TEM operates on the same basic principles as the light microscope but uses electrons instead of light. Because the wavelength of electrons is much smaller than that of light, the optimal resolution attainable for TEM images is many orders of magnitude better than that from a light microscope. Thus, TEMs can reveal the finest details of internal structure - in some cases as small as individual atoms.

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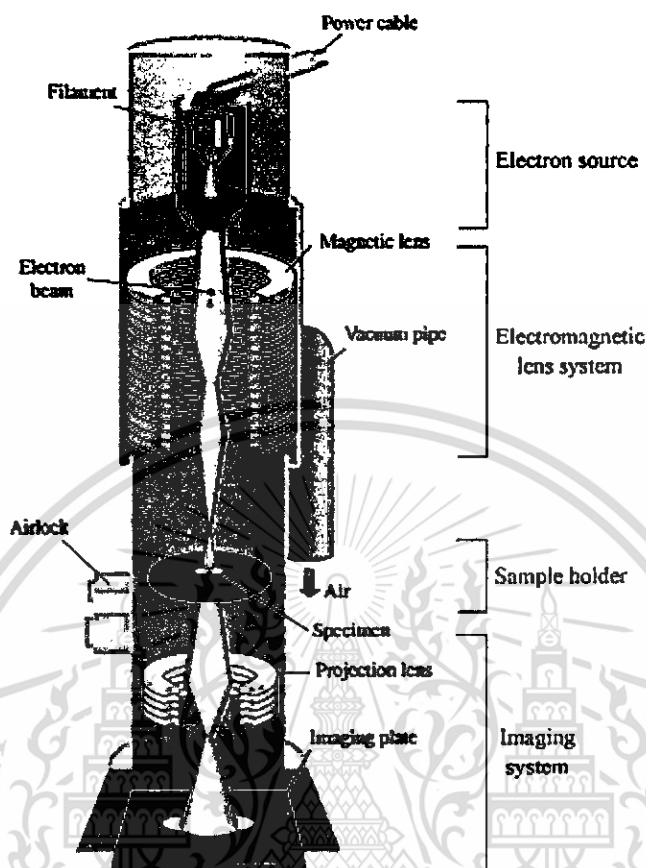


Figure 2.14 Schematics of transmission electron microscopy operation [15]

2.7.3 Thermogravimetric analysis

Thermogravimetric Analysis or Thermal Gravimetric Analysis (TGA) is a type of testing that is performed on samples to determine changes in weight in relation to change in temperature. Such analysis relies on a high degree of precision in three measurements: weight, temperature, and temperature change. As many weight loss curves look similar, the weight loss curve may require transformation before results may be interpreted. A derivative weight loss curve can be used to tell the point at which weight loss is most apparent. Again, interpretation is limited without further modifications and deconvolution of the overlapping peaks may be required. TGA is commonly employed in research and testing to determine

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characteristics of materials such as polymers, to determine degradation temperatures, absorbed moisture content of materials, the level of inorganic and organic components in materials, decomposition points of explosives, and solvent residues. It is also often used to estimate the corrosion kinetics in high temperature oxidation. Simultaneous TGA-DTA/DSC measures both heat flow and weight changes (TGA) in a material as a function of temperature or time in a controlled atmosphere. Simultaneous measurement of these two material properties not only improves productivity but also simplifies interpretation of the results. The complementary information obtained allows differentiation between endothermic and exothermic events which have no associated weight loss (e.g., melting and crystallization) and those which involve a weight loss (e.g., degradation). By figure 2.15 shown a schematics Thermogravimetric Analysis operation [16]

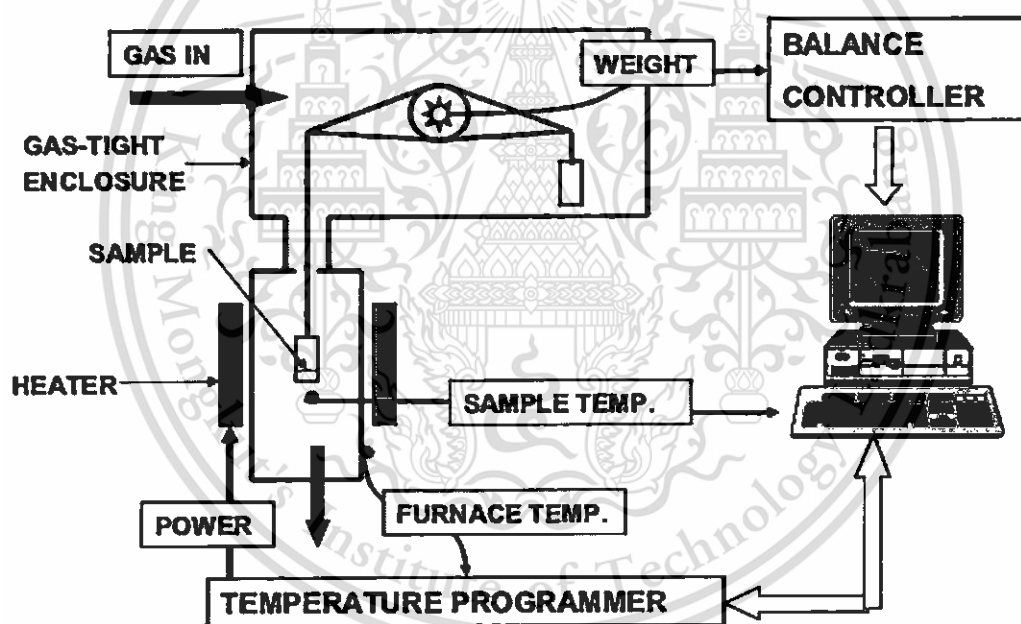


Figure 2.15 Schematics of thermogravimetric analysis operation [16]

2.8 Literature reviews

The main emission of diesel engine is particulate matter which emitted to atmosphere from exhaust gas. It is the major problem of air pollution and human health. So the study of particulate matter is an important thing and the result of them can be summarized as below:

M. M. Maricq (2007) [17] proposed the characteristics of the particulate matter from diesel engine. Figure 2.16 shown the diesel particulate matter consists of two types of particles: (a) fractal-like agglomerates of primary particles 15–30 nm in diameter, composed of carbon and traces of metallic ash, and coated with condensed heavier end organic compounds and sulfate; (b) nucleation particles composed of condensed hydrocarbons and sulfate.



Figure 2.16 Artist's conception of diesel particulate matter [17]

O. I. Smith (1981) [18] presented the basic structure of primary particles. A primary particle is consisted by carbon atoms which are bonded together in hexagonal face – centered arrays in planes, referred to as

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platelets. Platelets are arranged in layers to form crystallites. There are typically 2–5 platelets per crystallite, and on the order of 10^3 crystallites per spherical soot particle. The crystallites are arranged with their planes more or less parallel to the particle surface. This structure of unordered layers is called turbostatic. Spherules, diameter of 10–50 nm, are fused together to form particles. A single spherule contains 105 to 106 carbon atoms.

D. B. Kittelson (1997) [19] concluded the particulate matter composition and structure. Diesel exhaust particles consist mainly of highly agglomerated solid carbonaceous material and ash, and volatile organic and sulfur compounds. Solid carbon is formed during combustion in locally rich regions. Much of it is subsequently oxidized. The residue is exhausted in the form of solid agglomerates. A tiny fraction of the fuel and atomized and evaporated lube oil escape oxidation and appear as volatile or soluble organic compounds (generally described as the soluble organic fraction, SOF) in the exhaust. The SOF contains polycyclic aromatic compounds containing oxygen, nitrogen, and sulfur. Metal compounds in the fuel and lube oil lead to a small amount of inorganic ash. The idealized of diesel particles number and mass weighted size distributions. Most of the particle mass exists in accumulation mode in the 0.1 - 0.3 μm diameter range. This is where the carbonaceous agglomerates and associated adsorbed materials reside. The nuclei mode typically consists of particles in the 0.005 - 0.05 μm diameter range. This mode usually consists of volatile organic and sulfur compounds that form during exhaust dilution and cooling, and may also contain solid carbon and metal compounds. The nuclei mode typically contains 1 - 20% of the particle mass and more than 90% of the particle number. The coarse mode contains 5 - 20% of the particle mass. It consists of accumulation mode particles that have been deposited on cylinder and exhaust system surfaces and later re-entrained.

Y. Songsaengchan et al (2012) [20] investigated the chemical characteristic of biodiesel and diesel particulate matter at various engine loads (0%, 50% and 80%). The research result represented particulate matter of diesel combustion is consisted approximately 4% moisture, 71% unburned HC and 25% carbon of no-load condition, 50% load condition is 6% moisture, 46% unburned HC and 48% carbon and 80% load condition is 4% moisture, 29% unburned HC and 67% carbon while particulate matter of biodiesel combustion is consisted approximately 4% moisture, 86% unburned HC and 10% carbon of no-load condition, 50% load condition is

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9% moisture, 66% unburned HC and 25% carbon and 80% load condition is 4% moisture, 40% unburned HC and 56% carbon. The biodiesel engine particulate matter is faster oxidized than that of diesel engine particulate matter. In addition, the engine particulate matter from low load condition is faster oxidized than higher load for both of diesel and biodiesel fuels. So, particulate matter in high load condition has lower unburned HC fraction than that lower load condition. The combustion temperature in high load condition is more than that of low load. The unburned HC might be oxidized with remain oxygen in high temperature exhaust gas. Moreover, particulate matter from biodiesel engine combustion has more unburned HC fraction than that of diesel engine combustion. Biodiesel fuel has lower heating value than that of diesel fuel. In the same load condition, biodiesel must be used more fuel injection in combustion chamber in combustion duration. More of fuel remaining in combustion duration is burned to be more HC in particulate matter.

A. K. Agarwal et al. (2011) [21] studied the effect of particulate matter emitted from a mid-size engine running on petroleum-based diesel versus biodiesel. They found that biodiesel and its blends (B20) gave more SOF in engine exhaust particulates than mineral diesel at all operating conditions because biodiesel has more viscosity value than mineral diesel so biodiesel drop was combusted harder than mineral diesel. But all operating conditions of studies, the peak particle for B100 and B20 were always smaller size than mineral diesel because of oxygen atom in fuel molecule.

T. Lu et al (2012) [22] analyzed the size and nanostructure of particulate matter that Effects from engine operating conditions by using transmission electron microscope (TEM). This research revealed that the size of primary particles is determined by the combustion conditions. It is found that primary particle size decreases with engine speed as a consequence of the shorter combustion duration but increases with increase of engine load (as reflected by a decrease in the air/fuel ratio) due to the longer duration of diffusion combustion and higher combustion temperature.

H. Kim et al. (2010) [23] explored the effect of biodiesel blended diesel fuel on nanoparticles. The number of particles smaller than 50 nm was increased under 5% and 20% biodiesel–diesel blends (BD05 and BD20) in comparison with diesel (D100). The number of particles smaller than 50 nm was increased by 8.7% (1.6%) when migrating from D100 to BD05 (BD20). With respect to particles smaller than 100 nm, the use of BD05 exhibited a

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5.4% - higher particle number concentration than that of D100; however, under BD20, the corresponding value was 6.3% less than under D100. Therefore, compared with the particle number concentration under D100 there are more particles smaller than 50 nm – but fewer large particles – were emitted under BD20. The increased number of particles less than 50 nm that were emitted through the use of biodiesel–diesel blends possibly originated from the increase in the SOF particles. Under BD05, the rate of reduction in particle numbers in the catalyst was higher than that under D100, probably because a large number of SOF particles were oxidized in the oxidation catalyst. The total number of particles emitted under BD05 in the entire range of measurement ($10 < D_p < 385$ nm) increased by 4.4%. However, under BD20, the corresponding number decreased by 9.4%, and in terms of the converted particle weight, the particle mass reduced by 25%. The use of biofuel-blended diesel fuels reduced the total number of particles emitted from the engine. However, when compared to the use of diesel, the use of biodiesel–diesel blends caused the emission of more particles smaller than 50 nm, which are harmful to human body.

D. Dwivedi et al. (2006) [24] investigated about characterization particulate emissions from diesel engines fuelled by mineral diesel and B20 which operated at idling, 25%, 50% and 75% engine load. They found that oxygenated fuel B20 (biodiesel blend) showed superior engine performance in reducing particulate emissions at all operating conditions compared to mineral diesel (particulate in DE; 22–59 mg/m³ and in BDE; 17–48 mg/m³). This may be due to lower sulphur and aromatic content of biodiesel.

M. Salamanca et al. (2012) [25] attempted the influence on the chemical composition of the particle matter produced in an automotive diesel engine operated with palm biodiesel (PB100) and its blends with diesel fuel by 5%, 20% and 50% of biodiesel. The result shown that biodiesel does not affect significantly the average size of PM emitted compared to diesel. However, biodiesel and biodiesel-diesel blends tend to produce PM with a higher number of diameters below 25 nm. In general, the higher oxygen content of biodiesel affects the chemical and morphological characteristics of the particulate matter produced in diesel engines.

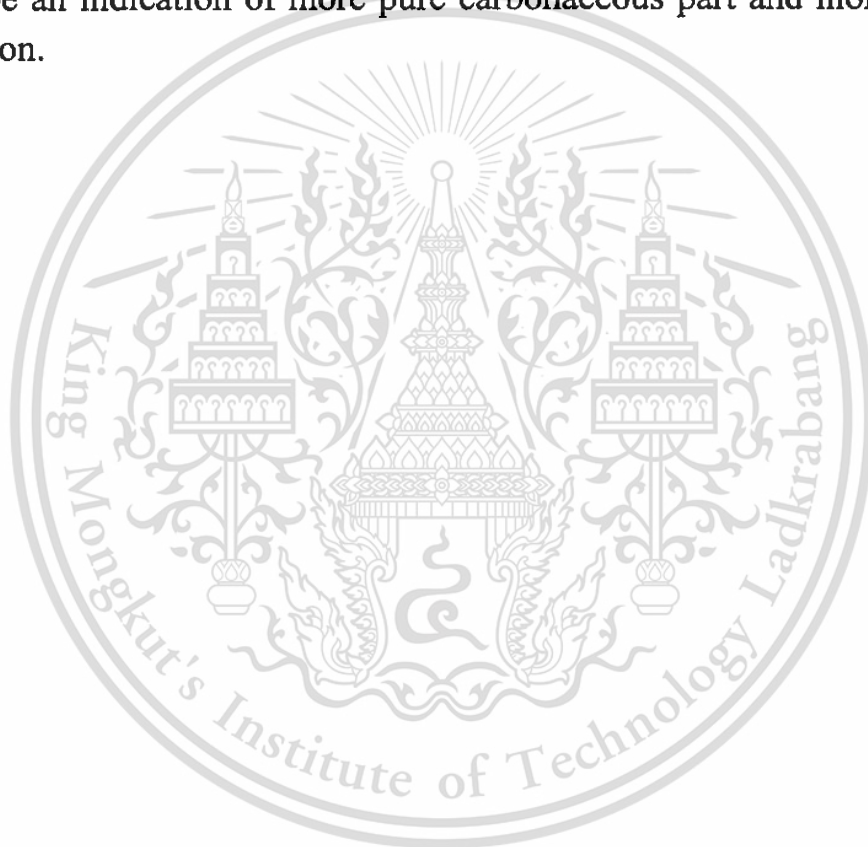
P. Karin et al. (2012) [26] cultivated the particulate matter trapping which emitted from biodiesel and diesel fuel by using conventional diesel particulate filter (DPF). The studies presented DPF trapping duration of biodiesel fuel has longer than that of diesel fuel around two times because of

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PM concentration emitted from bio-oxygenated fuel combustion frame is lower than that of diesel combustion. Due to biodiesel fuel consisting of more oxygen atom in fuel molecule is readily oxidized with available oxygen in the flame zone.

M. Borhanipour et al. (2014) [27] assayed the biodiesel and diesel particulate matter oxidation by thermogravimetric analyzer (TGA) in the isothermal condition. PM composition in biodiesel PM and diesel PM also has noticeable effect on activation energy (E_a). The difference of E_a at 80-60% and 60-40% fraction can be referred to difference in amount and type of HC and elemental composition while at (40-20%) stage the results get closer and can be an indication of more pure carbonaceous part and more similar composition.



Chapter 3

EXPERIMENTAL APPARATUS AND PROCEDURE

3.1 Experimental apparatus

3.1.1 Diesel engine specification

The small diesel engine was used for produce particulate matter in condition of diesel and biodiesel fuel which is four stoke, single cylinder, 638 cm³ displacement, direct injection and 16.1:1 compression ratio. Fuel injection pressure is 19.6 MPa and other specification is shown in Figure 3.1. The engine was operated and controlled on eddy current dynamometer (Tokyo Plant ED-60-LC at KMITL).

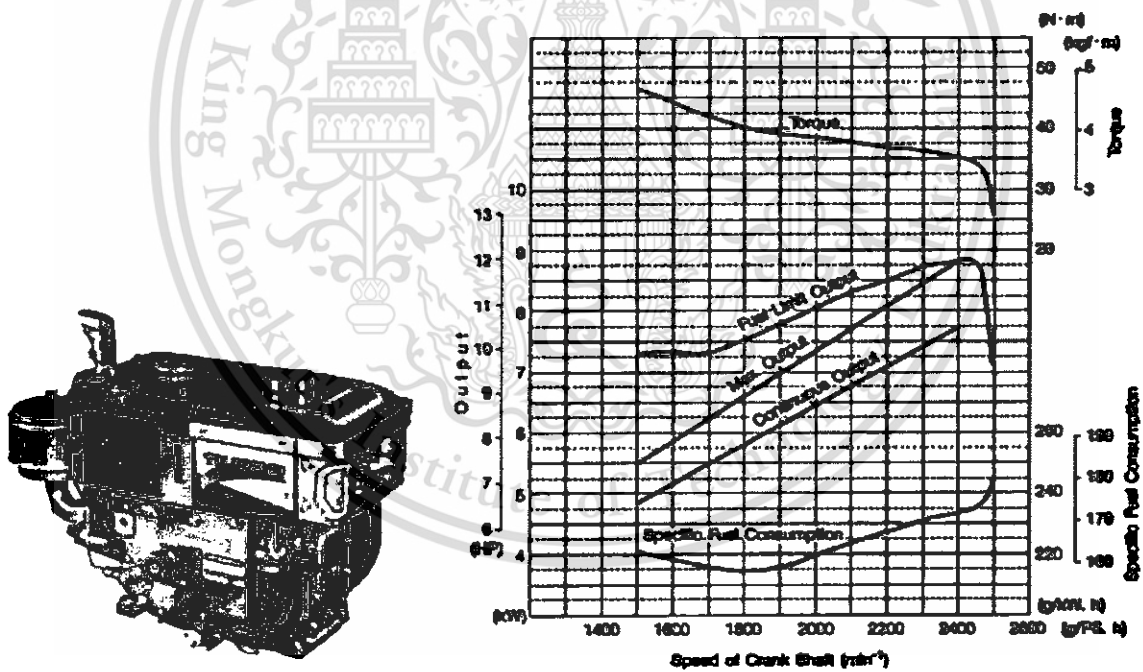


Figure 3.1 Diesel engine and specification

3.1.2 Eddy Current Engine Dynamometer

The engine dynamometer, Tokyo Plant model ED-60- Horizontal, was used in the experiment for applying a load on the tested engine and also measuring force, moment of force (torque) and power that the tested engine can produce against the load. The type of the engine dynamometer is Eddy current with external water cooling systems. Eddy current dynamometer can provide a quick load change rate for rapid load setting. Eddy current dynamometer consists of an electrically conductive core moving across a magnetic field to produce resistance to movement. The magnetic field is generated by using variable electromagnets that can change the magnetic field strength to control the amount of braking. The electromagnet voltage is control by a desktop computer, using changes in the magnetic field to match the power output.

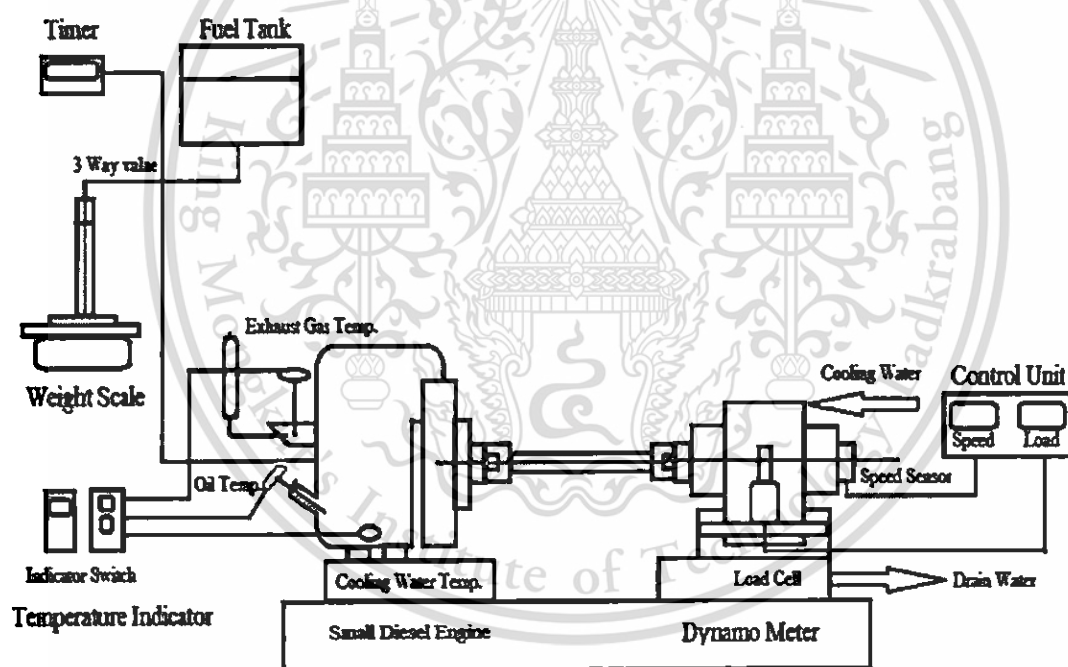


Figure 3.2 Schematic diagram of engine dynamometer

3.1.3 Fuel specification

This research is used fuel in two types such as conventional diesel fuel and palm-oliem biodiesel. The all of results from both fuels were used for compare in all of condition for testing. The fuels properties are shown in table 3.1 and 3.2

Table 3.1 Diesel fuel properties

Test Parameter	Result
Appearance	Clear & Bright
Calculated Cetane Index	55.5
API Gravity @60 °F, Average, °API	38.0
API Gravity @60 °F, Upper, °API	38.1
Specific Gravity 15.6/15.6 °C, Upper	0.8344
API Gravity @60 °F, Middle, °API	38.0
Specific Gravity 15.6/15.6 °C, Middle	0.8347
API Gravity @60 °F Lower, °API	38.0
Specific Gravity 15.6/15.6 °C, Lower	0.8346
API Gravity @60 °F, Bottom, °API	38.0
Pour Point, °C	-3
Flash Point, (P.M.), Upper, °C	64
Flash Point, (P.M.), Lower, °C	66
Sulfur Content, mg/kg	68
Distillation :Initial Boiling Point, °C	178.3
Distillation :10 %Vol. Recovered, °C	214.3
Distillation :50 %Vol. Recovered, °C	281.5
Distillation :90 %Vol. Recovered, °C	352.3
Kinematic Viscosity at 40°C,mm ² /s	3.092
Water and Sediment, % vol	<0.005
ASTM Color	L2.0
Gross Heat of combustion, BTU/lb	19,703
Methyl Ester of fatty Acid, % vol.	4.7

Table 3.2 Biodiesel fuel properties

Test Parameter	Result
Methyl Ester, %wt	97.9
Density at 30°C, kg/m ³	864.1
Viscosity at 40°C, cSt	4.5
Flash Point, °C	184.5
Sulphur Content, %wt	< 0.0001
Carbon, on 10% distillation residue, %wt	< 0.1
Cetane Number	68.2
Sulphated Ash, %wt	< 0.001
Water, %wt	0.028
Total Contaminate, %wt	0.0003
Copper Strip Corrosion, %wt	1a
Oxidation Stability at 110 °C, hr	26.3
Acid Value, mgKOH/g	0.1
Iodine Value, gI ₂ /100g	51.5
Linolenic Acid Methyl Ester, %wt	0.18
Methanol, %wt	0.03
Monoglyceride, %wt	0.31
Diglyceride, %wt	0.05
Triglyceride, %wt	0.01
Free Glycerin, %wt	0.00
Total Glycerin, %wt	0.09
Group I metals, mg/kg	0.39
Group II metals, mg/kg	0.69
Phosphorus, %wt	<0.00001
Additive	No
Appearance	Clear
Cloud Point, °C	14.0

Figure 3.3 explains about the distillation curve of fuel test. The diesel fuel can be distilled easier at low temperature than biodiesel fuel because diesel fuel has many size of fuel molecule. Most of diesel fuel is single component, so can be vaporized at the low temperature. In opposite to, the biodiesel fuel is multiple component and mostly homogeneous which can be

distilled in the constant temperature around 350 degrees Celsius more than diesel fuel.

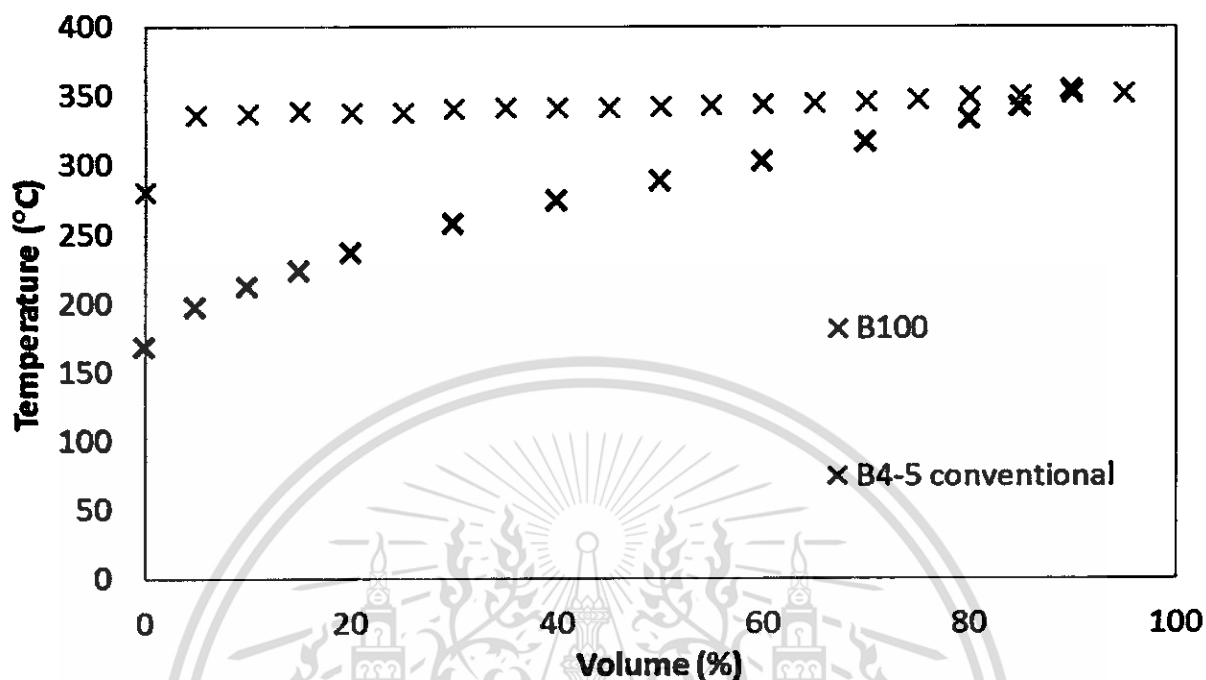


Figure 3.3 Distillation of conventional diesel and biodiesel fuel

3.1.4 Particulate matter trapping equipment

The trapping equipment was used for the study of diesel and biodiesel particulate matter trapping mechanism. The schematic diagram of trapping system is shown in figure 3.4. The particulate filter box was installed in the pipe which connected to the small diesel engine exhaust pipe. The exhaust gas was flown into the small particulate filter through a bypass line. The process was operated at constant temperature which controlled by furnace. The quantity of particulate matter that trapped on particulate filter was measured by pressure sensor which determined the difference pressure between before and behind particulate filter and vacuum pump was used for the control of constant pressure in trapping process. All of data was kept by data acquisition system.

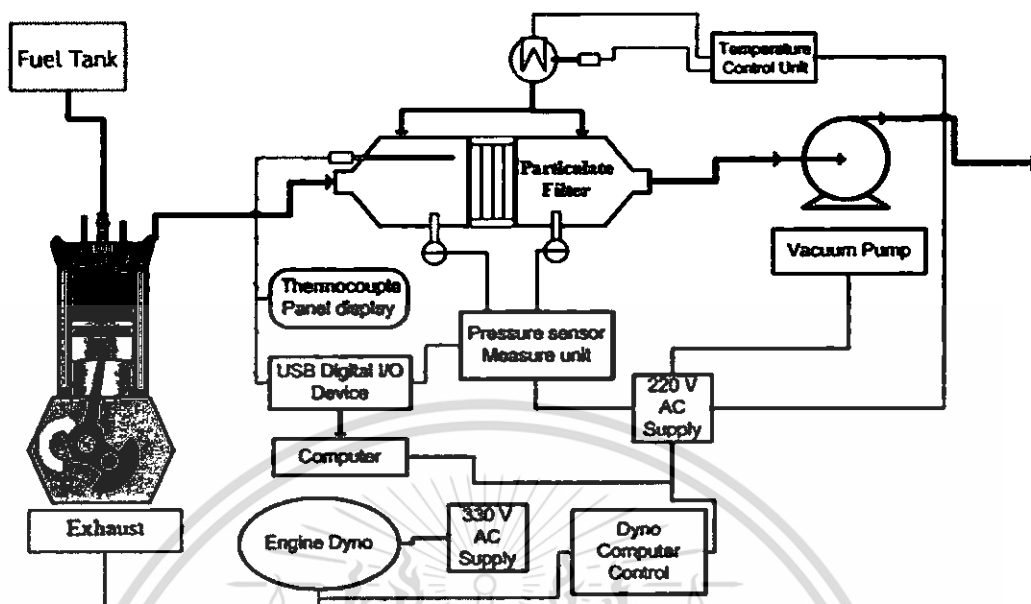


Figure 3.4 Schematic diagram of trapping system

3.1.5 Particulate filter regeneration

In the regeneration equipment was used for the study of particulate filter regeneration mechanism. The schematic diagram of regeneration system is shown in figure 3.5. After the engine stopped and particulate filter was full, nitrogen and oxygen gas was released through the small particulate filter for oxidation with particulate matter which controlled by furnace at constant temperature and the gas flow rate in regeneration process was controlled by flow switch. The quantity of particulate matter that oxidized on particulate filter was measured by pressure sensor which determined the difference pressure between before and behind particulate filter. All of data was kept by data acquisition system.

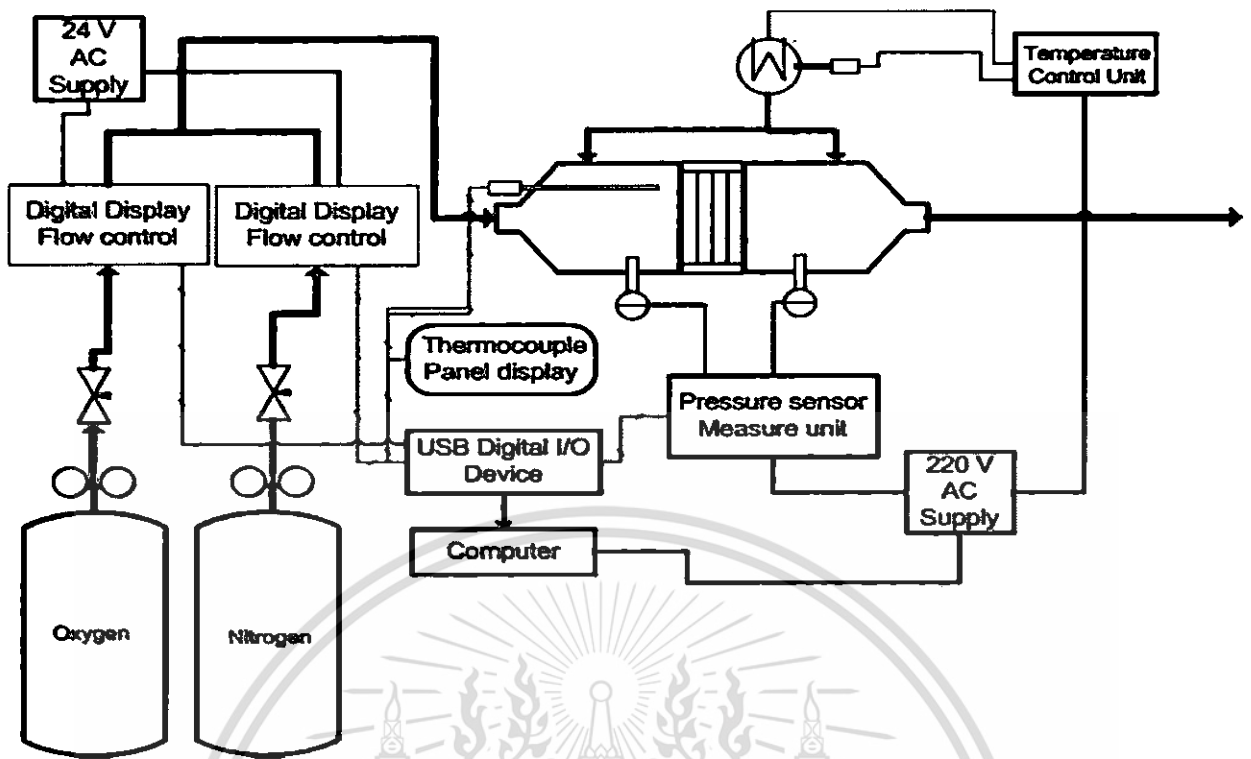


Figure 3.5 Schematic diagram of regeneration system

3.1.6 Diesel particulate filter (DPF)

A sample of conventional diesel particulate filter used as the trapping device. The technical data and the picture of the diesel particulate filter is shown in table 3.3 and figure 3.6.

Table 3.3 Diesel particulate filter specification

Properties/Type	Ceramics cordierite
Wall thickness	300 micrometer
Porosity (%)	52%
Average pore size	10 - 50 micrometer
Cell density (cps)	300

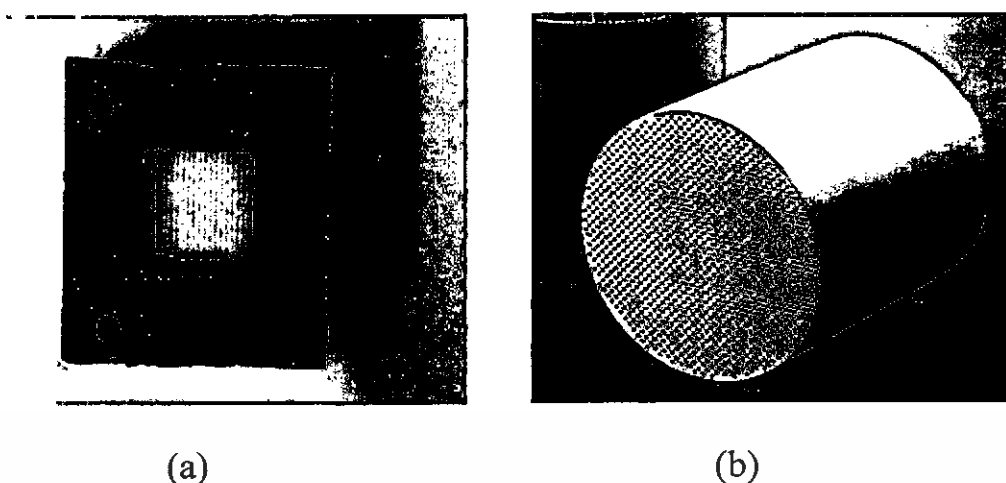


Figure 3.6 (a) A cut of particulate filter sample. (b) The conventional diesel particulate filter

3.1.7 Temperature control system

When the particulate matter flow from exhaust pipe to trapped on particulate filter, the temperature was controlled by a high temperature furnace approximately $200\text{ }^{\circ}\text{C}$ which shown in figure 3.6 in this study for keep temperature inside filter as close to real exhaust gas temperature in the engine. In the regeneration process in order to provide enough temperature for soot oxidation around $600\text{ }^{\circ}\text{C}$ inside the particulate filter, a high temperature furnace was applied at this study. Thus, control system for keep the temperature constant is necessary. A type K thermocouple, which is tuned 0-10 V to DAQ with a transmitter TM – 004 controllers is used. The head of thermocouple is put as close as possible to particulate filter, in order to measure the temperature particulate filter surrounding inside the pipe. A picture of thermocouple and its controller is shown in figure 3.7.

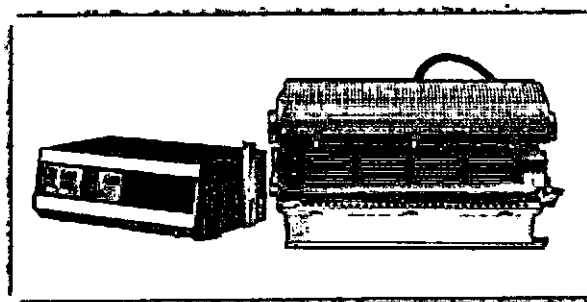


Figure 3.7 High temperature furnace

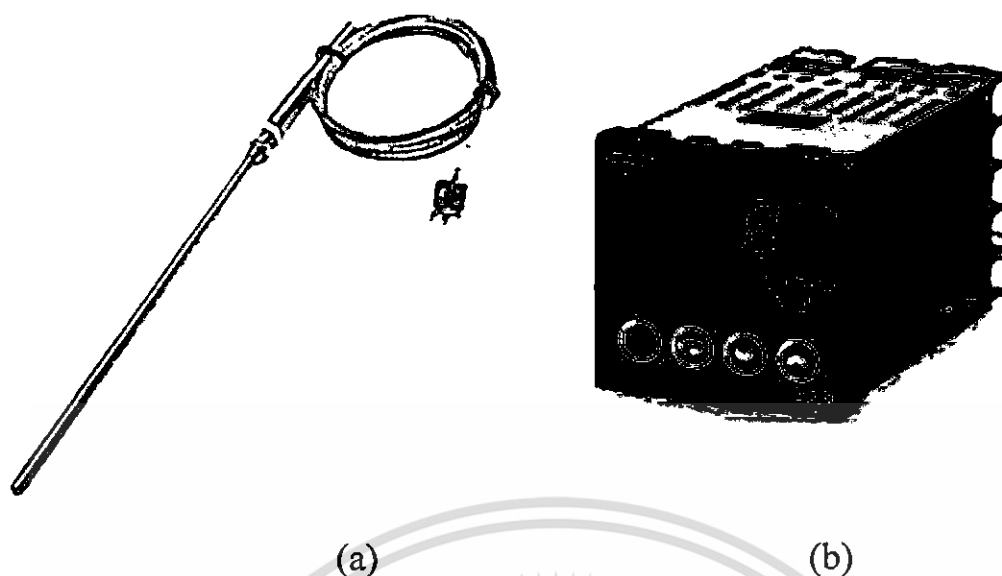



Figure 3.8 (a) Thermocouple type K. (b) Temperature controller

3.1.8 Different pressure sensor

Differential pressure sensor is used for measure pressure drop between inlet and outlet of the particulate filter. The pressure drop is effect back to the engine while particulate matter in exhaust gas is trapped in the filter. Particulate matter quantities can be measured by back pressure increasing. Moreover, the oxidation kinetic of particulate matter in the filter is also investigated by decreasing pressure when exhaust gas temperature is appropriated. Figure 3.8 shows differential pressure sensor which is used in the experimental.



Characteristic	Symbol	Min	Typ	Max	Unit
Pressure Range	P_{cp}	0	-	50	kPa
Supply Voltage	V_s	4.75	5	5.25	V _{dc}
Supply Current	I_o	-	7	10	mA _{dc}
Minimum Pressure Offset @ $V_s = 5.0$ Volts (0 - 85 °C)	V_{off}	0.088	0.2	0.313	V _{dc}
Full Scale Output @ $V_s = 5.0$ Volts (0 - 85 °C)	V_{fso}	4.587	4.7	4.813	V _{dc}
Full Scale Span @ $V_s = 5.0$ Volts (0 - 85 °C)	V_{fss}	-	0.5	-	V _{dc}
Accuracy (0 - 85 °C)	-	-	-	± 2.5	%V _{fss}
Sensitivity	V/P	-	90	-	mV/kPa
Response Time	t_r	-	1	-	ms
Output Source Current at Full Scale Output	I_{o+}	-	0.1	-	mA _{dc}
Warm - Up Time	-	-	20	-	ms
Offset Stability	-	-	± 0.5	-	%V _{fss}

Figure 3.9 Differential pressure sensor and specification

3.1.9 Vacuum Pump

Vacuum Pump model DV-300 Aspirator was used for the control flow rate exhaust gas in trapping process which installed in the end of pipe behind particulate filter. A picture and specification of vacuum pump is shown in figure 3.10.

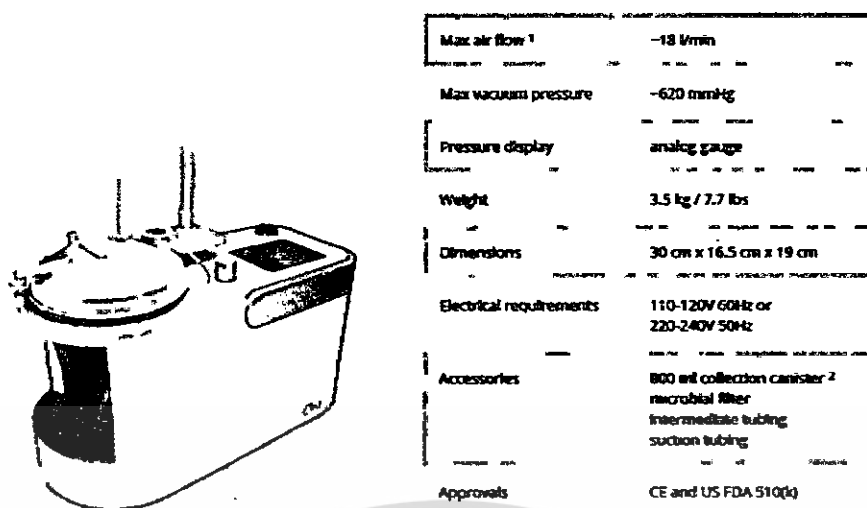
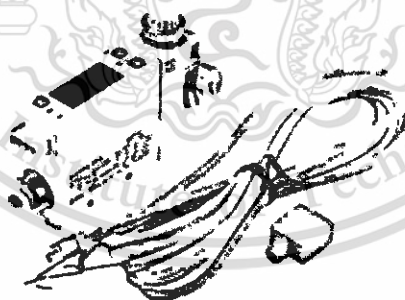


Figure 3.10 Vacuum pump and specification

3.1.10 Digital flow switch

A digital flow switch model PFM725S-N01-E was used for control oxygen and nitrogen gas in particulate filter regeneration by oxygen gas will flow through small particulate filter to oxidize with particulate matter that trapped on particulate filter to be a carbon dioxide gas. A picture and specification of digital flow switch is shown in figure 3.11.



Model	Rated flow range (l/min)	Displayable range (l/min)	Settable range (l/min)	Max. analog output	
				Voltage (V _{max})	Current (I _{max})
PFM725	0.5 to 25.0	0.5 to 26.3	0 to 26.3	5.00 V	20.0 mA

Figure 3.11 Digital flow switch and specification

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3.1.11 Data acquisition system

The pressure drop and temperature during the particulate matter filtration in the experiment was kept by data acquisition system. This system was controlled by National Instruments DAQ card series 6009 as shown in figure. 3.12. A data acquisition card was programmed by LabVIEW program. A 0 - 5 V pressure signal from differential pressure sensor connected to DAQ card and monitored 0 - 45 kPa for pressure drop between before and after the filter in the experiment. In addition, the temperature of exhaust gas signal from type K thermocouple which was amplified to 0 - 10 V by thermocouple transmitter TM - 004 was connected to DAQ card and shown an exhaust gas temperature on display monitor as show in figure 3.13.

Moreover, a pressure drop and temperature from data acquisition system can be recorded to law data for used to analyze trapping mechanism of diesel and biodiesel particulate and regeneration mechanism of particulate filter.

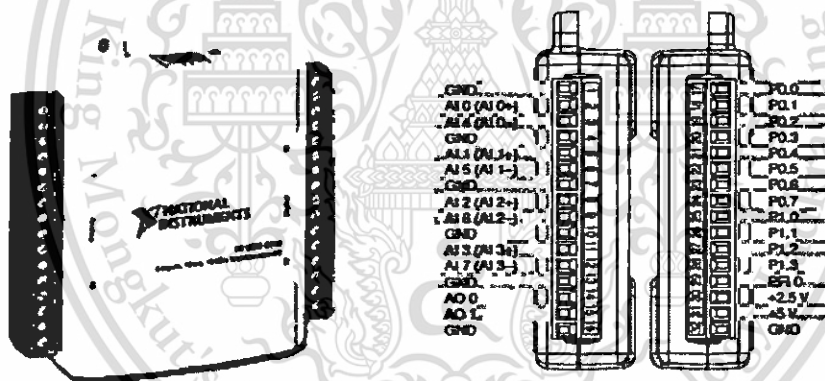
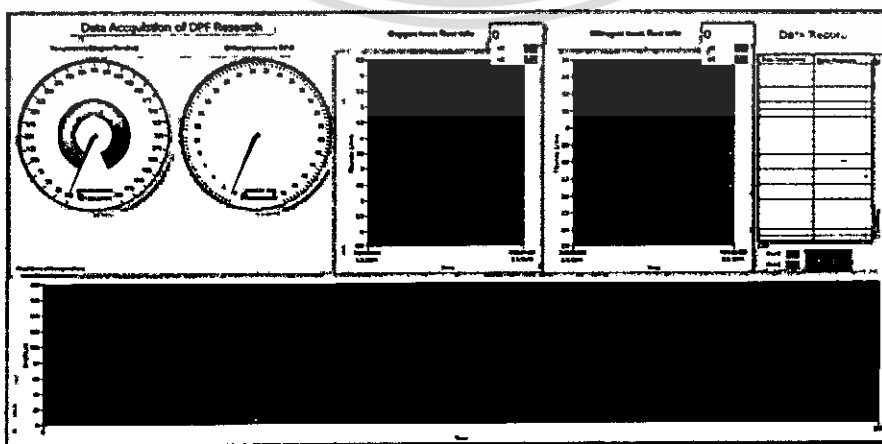


Figure 3.12 Data acquisition system (DAQ) National instrument 6009



This material is resealed **Figure 3.13** Data acquisition monitor for commercial use.

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3.1.12 Black smoke meter

Particulate matter emitted from engine combustion is measured in black smoke percentage. The smoke meter is applied to measure the concentration between particulate matter in exhaust gas before the filter and remaining after trapping in particulate filter by light emitting method. The zero percentage black smoke mean that is no particulate on filter and the other hand 100 percentage is mean the filter is covered by particulate all of area. This smoke meter percentage can be summarized that the filtration efficiency of particulate filter. However, the smoke meter, Okuda DSM - 240, is shown in figure 3.14 which is used in investigation of particulate matter concentration and particulate filter efficiency.



Figure 3.14 Smoke meter

3.2 Experimental condition

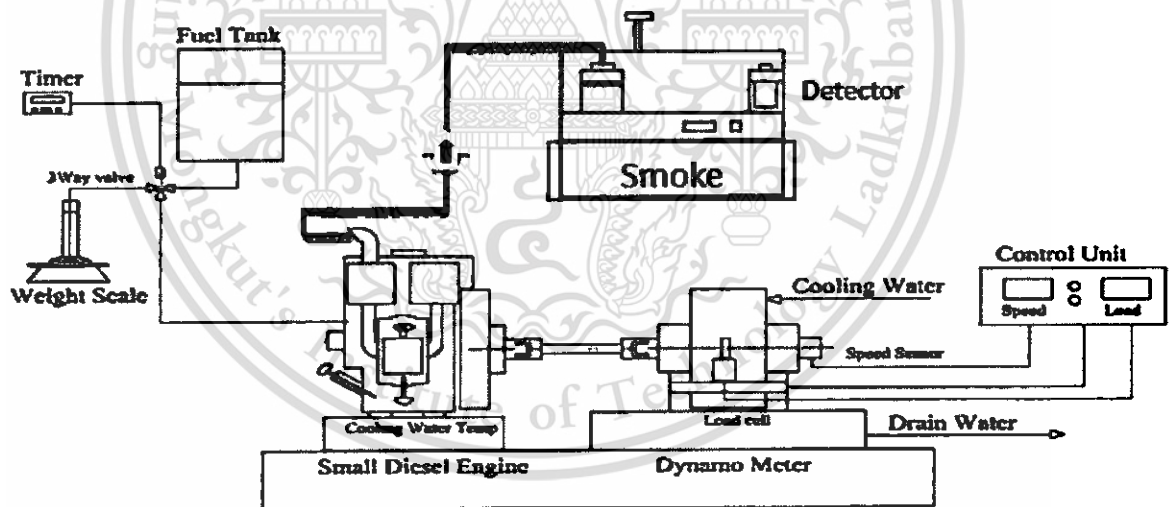
The diesel and biodiesel fuel was combusted in small diesel engine's combustion chamber to produce particulate matter. The diesel and biodiesel particulate matter was analyzed for physical and chemical characteristic which consist of scanning electron microscope (SEM), transmission electron microscope (TEM) and thermogravimetric analysis (TGA). The quantities of particulate matter were investigated by smoke meter and air filter. Finally, the particulate matter was tested for trapping mechanism which resulted in pressure drop during particulate matter clogging in filter and oxidation during regeneration process in the experimental. The experimental condition of each topic is shown in the table 3.4.

Table 3.4 Experimental condition

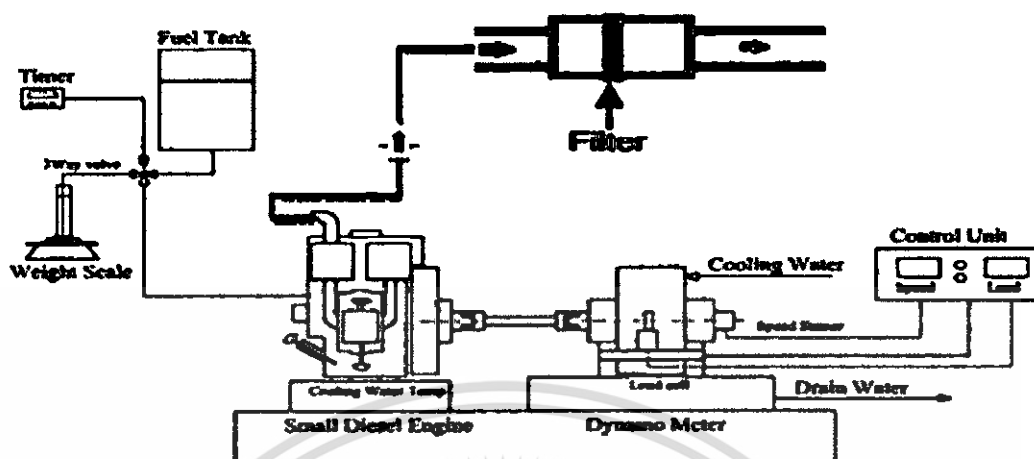
Topic	Engine load (%)	Engine Speed (rpm)	Fuel
Smoke meter	20	1600	Diesel Biodiesel
SEM	40	2000	
TEM	60	2400	
	80		
Air filter	80	2400	Diesel Biodiesel
TGA			
Trapping			
Regeneration			

3.3 Experimental procedure

3.3.1 Particulate matter quantities



(a)



(b)

Figure 3.15 (a) Smoke meter and (b) air filter trap particulate matter in exhaust gas

The particulate matter quantities were investigated by the percentage of smoke meter and mass of particulate on air filter. The particulate matter was trapped by the smoke meter device and filter while it suspended in exhaust gas in condition. The results of diesel particulate matter concentration were compared with the results of biodiesel particulate matter concentration at all of. The white paper filters were used for trapping particulate matter in exhaust gas to measure by light emitting method. The results of particulate mass on air filter were used for calculation of particulate matter that emitted from exhaust gas by gram per minute.

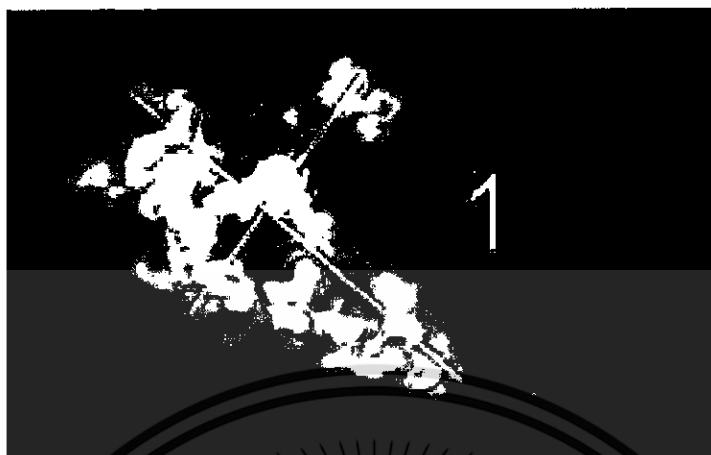
3.3.2 Particulate matter size distribution

The accumulated particulate matters from diesel and biodiesel engine combustion were trapped by paper filter for a few second. A paper filter was taken image in micro - scale with scanning electron microscope. The accumulated particulate matter images were measured size by average of two diagonal lengths as shown in figure 3.16. Approximately 60 particles was measured and analyzed for accumulated particulate matter size distribution.

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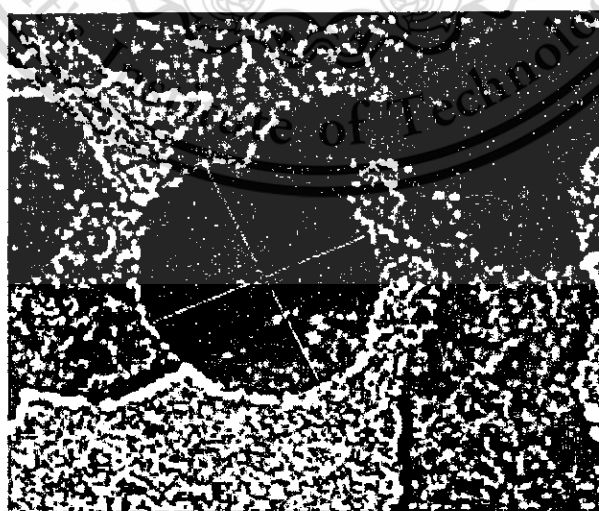
The results were compared between diesel and biodiesel. Moreover, it was also analyzed an effect of engine load and speed to particulate matter size.



$$\text{Average Dimeter} = \frac{D_1 + D_2}{2}$$

Figure 3.16 Agglomerate particulate matter measurements

A powder of particulate matter from diesel and biodiesel engine combustion was taken image in Nano - scale by transmission electron microscope. These images were measured for a particulate matter primary size for approximately 100 particles by average of two diagonal lengths as shown in figure 3.17. The result showed a comparison of primary size distribution of diesel and biodiesel particulate matter and effect of engine load and speed to engine particulate matter size.



$$\text{Average Dimeter} = \frac{D_1 + D_2}{2}$$

Figure 3.17 Primary particulate matter measurements

3.3.3 Particulate matter oxidation kinetic

The particulate matter powder from diesel and biodiesel engine combustion in each load condition was analyzed by thermogravimetric analysis (TGA) with isothermal method. The mass reduction rate with temperature results from TGA were investigated the oxidation kinetic and chemical consistent. The isothermal method was increasing rate of 0.5 °C per second from 30 °C to 500, 550 and 600 °C while the increasing of temperature from 30 °C to final, nitrogen gas was released to prevent the oxidation of particulate matter and after that air was release to oxidize with particulate matter. For the chemical consistent, the moisture, unburned hydrocarbon and carbon fraction inside the particulate matter from diesel and biodiesel engine were determined from the oxidation temperature. Moisture and hydrocarbon are oxidized in first phase at low temperature. Carbon is oxidized in phase.

3.3.4 Trapping and regeneration test

The trapping of diesel and biodiesel particulate matter was operated by small diesel engine on engine dynamometer which tested in 2400 rpm and 80% load condition. This process, the furnace was set to 200 °C and the pump was started to suck the particulate matter from exhaust gas to trap on particulate filter. When the particulate was full, the temperature was increased up to 600 °C while the increasing of temperature, gas nitrogen was released to the system. After that oxygen gas was released to mix with nitrogen gas by the gas flow rate was 13.5 l/min and change percentage of oxygen gas in 10, 15 and 21% to oxidize with particulate matter. A figure 3.18 is shown the device of this testing.

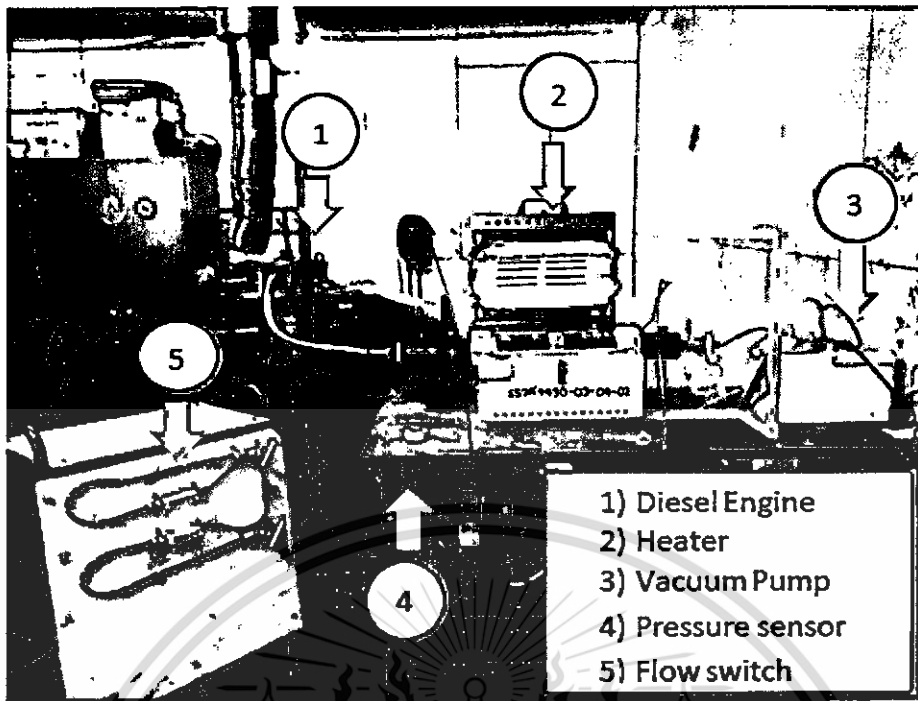


Figure 3.18 the device of trapping and regeneration testing

Chapter 4

RESULTS AND DISCUSSION

4.1 Physical characteristic

4.1.1 Particulate matter concentration

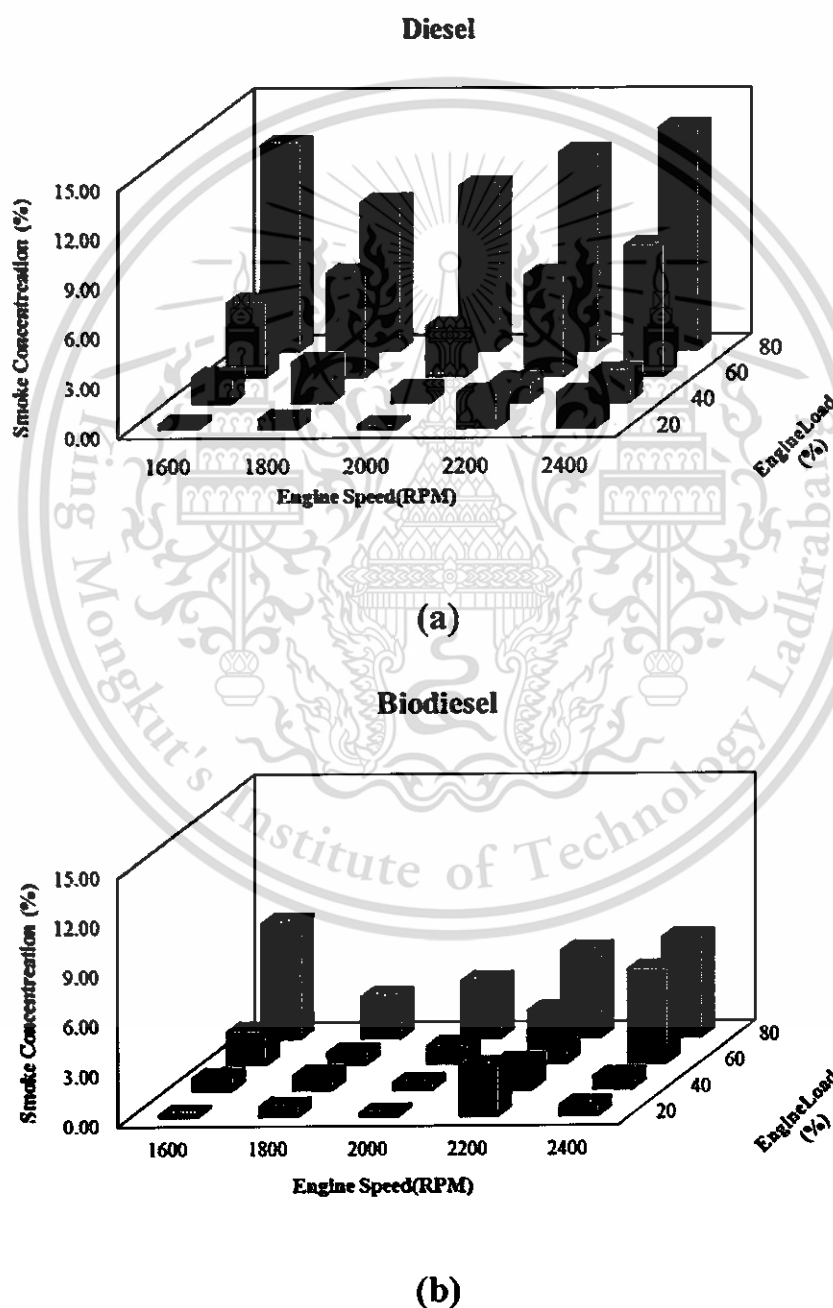


Figure 4.1 Black smoke percentage of particulate matter from engine exhausts gas (a) Diesel and (b) biodiesel

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The particulate matter was generated by the diesel engine and emitted to the atmosphere with the exhaust gas. The particulate matter from engine condition was emitted with the difference concentration as shown in figure 4.1. The black smoke percentage confirms that the diesel engine is darker than that of biodiesel engine (for the engine condition). The particulate matter in middle engine speed is lower than low and high engine speed because the middle engine speed is the condition of lowest engine energy consumption by the energy at low engine speed loss from heat lost and the energy at the high engine speed loss from friction lost that mean the amount of fuel at low and high engine speed are higher. In addition to, the particulate matter in high load condition is generated more than that of low load condition because the injection amount of fuel injection is higher. From the increasing of fuel in combustion chamber is a reducing overall air/fuel ratio. This condition makes incomplete combustion and encourages the initial particulate matter formation. Moreover, the higher of fuel injection makes bigger rich zone in fuel spray. These also make particulate matter formation in combustion chamber.

4.1.2 Particulate matter quantities

The particulate matter quantities from the diesel and biodiesel were trapped by filter for 10, 20, 30 and 40 second. The filters were weighted before and after the trapping to calculate the particulate matter mass flow rate which emitted from the combustion. The average particulate matter of biodiesel was around 0.06-0.07 g /min while diesel PM's flow rate was approximately twice, around 0.12-0.13 g/min as shown in figure 4.2. The main cause might be that biodiesel fuel contains lower number of carbon - carbon bonds compared to diesel fuel. A fuel with a large number of carbon - carbon bonds has a tendency of increasing particulate matter forming. Conversely, oxygen content in a fuel promotes more completely combustion cause to decreases the tendency of particulate matter forming.

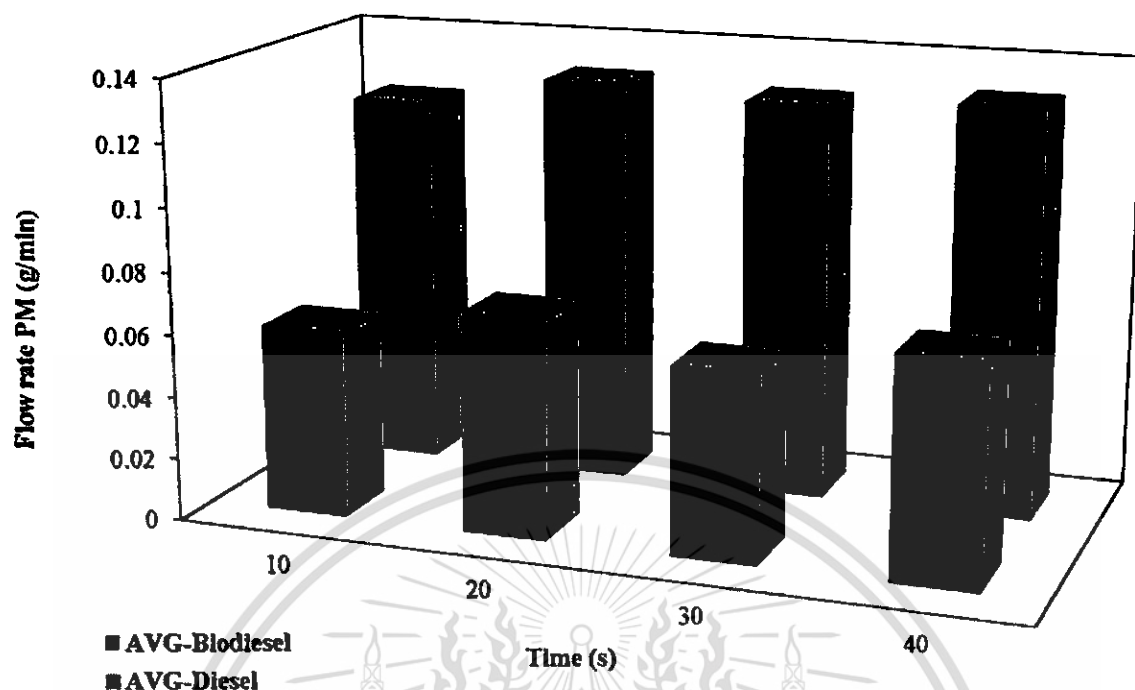


Figure 4.2 average particulate matter flow rate of diesel and biodiesel

4.1.3 Particulate matter morphology

The particulate matter emitted from diesel and biodiesel fuel in combustion process at 20, 40, 60 and 80% and 1600, 2000 and 2400 rpm. Condition was investigated for particle size distribution by the electron microscope. The particle size was measured by average of two diagonal lengths of approximately 100 particles.

4.1.3.1 Agglomerate size

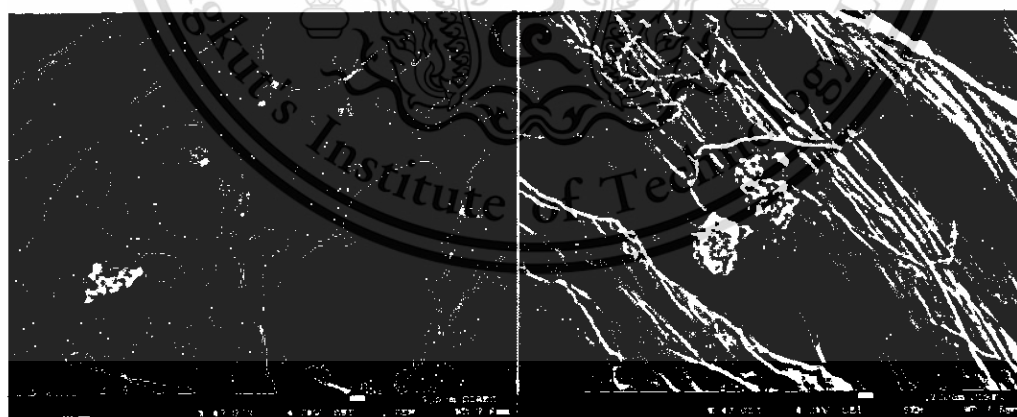
The particulate matter from diesel and biodiesel engine combustion in 20%, 40%, 60% and 80% load and 1600, 2000 and 2400 rpm condition was trapped by paper filter while it suspended on exhaust gas. A particulate matter on paper filter was taken image by scanning electron microscope and analyzed for agglomerate particle size distribution. Figure 4.3 shows particulate matter image from scanning electron microscope in various conditions. A particulate matter size distribution in agglomerate mode of diesel and biodiesel at engine speed 1600 rpm, 2000 rpm and 2400 rpm are

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shown in Figure 4.4 and 4.5 respectively. The particle sizes are in the range of 100-600 nm but much amount of particle sizes are in the range of 100-350 nm. Figure 4.6 shows Average size distribution of agglomerate particle particulate matter from diesel versus biodiesel under 20, 40, 60 and 80% of engine load and 1600, 2000 and 2400 rpm of engine speed particle diameter size decreased when increasing engine speed for both of diesel and biodiesel particulate matter. The exhaust gas temperature also gradually increased when increasing engine speed. It means particulate matter oxidation rate inside combustion chamber increased when increasing engine speed (increasing temperature) due to lower heat loss on cylinder surface compare to lower engine speed. Similarly, particle diameter size decreased when increasing engine load for both of diesel and biodiesel particulate matter. The exhaust gas temperature also gradually increased when increasing the engine load. It means particulate matter oxidation rate inside combustion chamber increased when increasing engine load (increasing fuel injection quantity) resulting in higher combustion temperature compare to lower engine load.

When focus on effect of biodiesel fuel and diesel fuel to the particulate matter size. The average of biodiesel particulate matte sizes are significantly smaller than that of because diesel is a bio-oxygenate fuel. So biodiesel can promote more complete combustion.



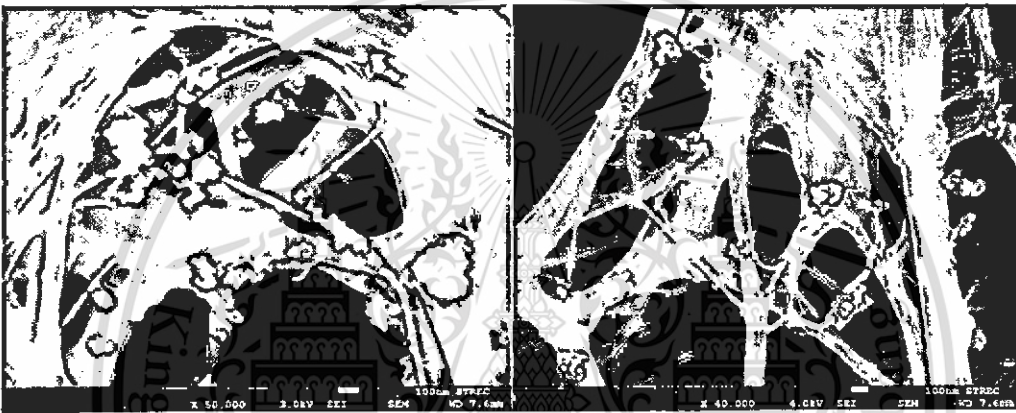
(a) 20%-1600

(m) 20%-1600



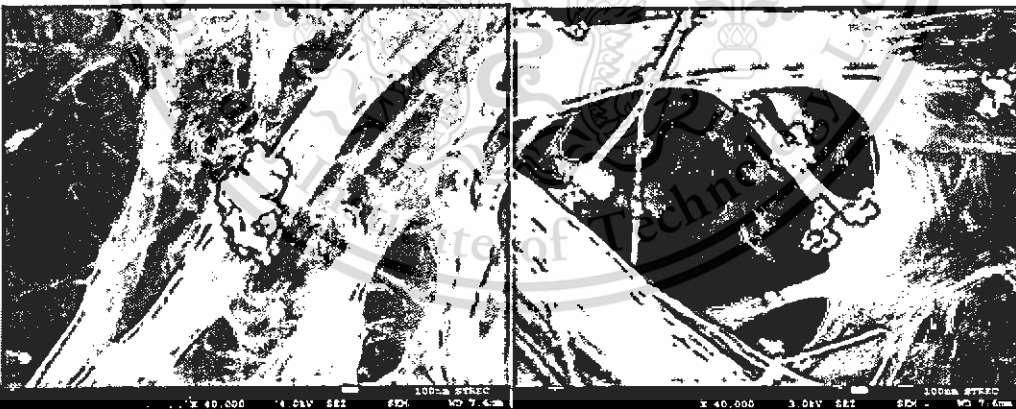
(b) 40%1600

(n) 40%1600



(c) 60%-1600

(o) 60%-1600



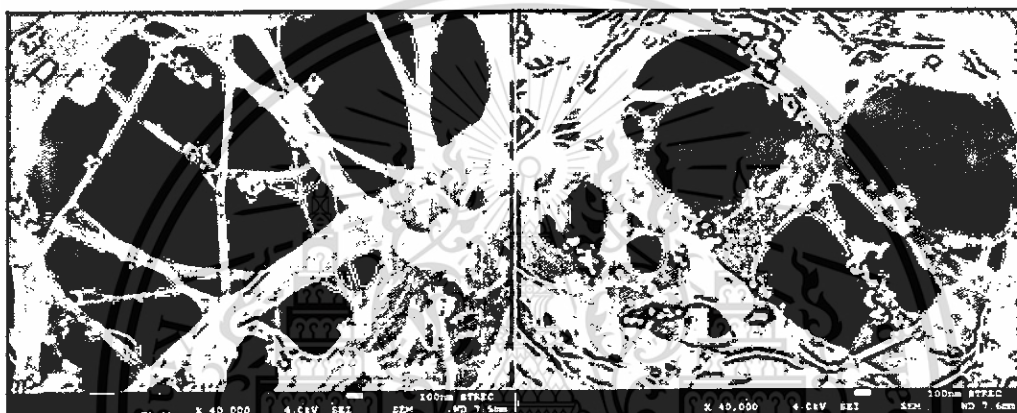
(d) 80%-1600

(p) 80%-1600



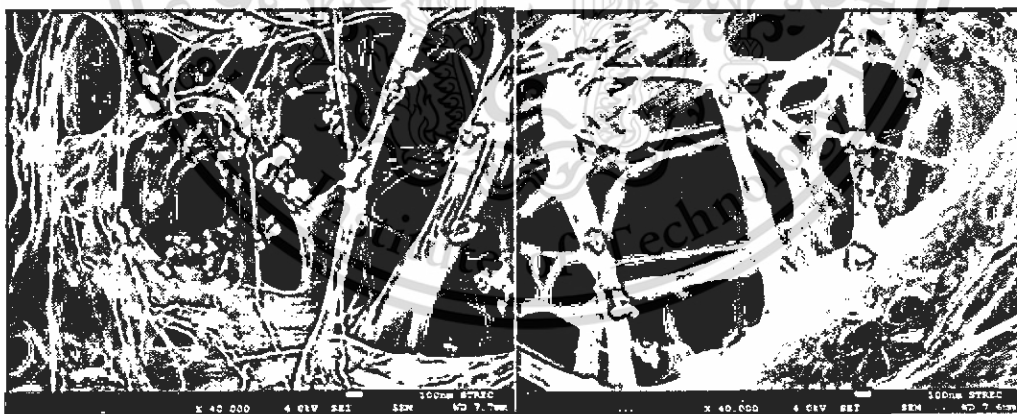
(e) 20%-2000

(q) 20%-2000



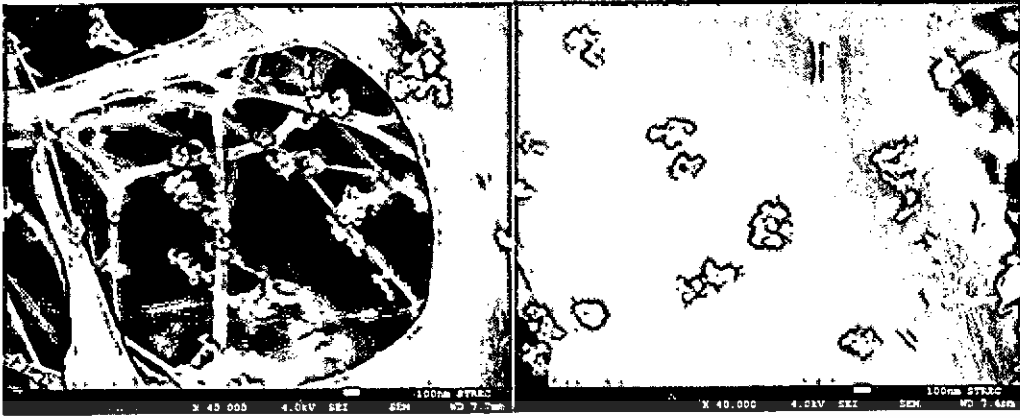
(f) 40%-2000

(r) 40%-2000



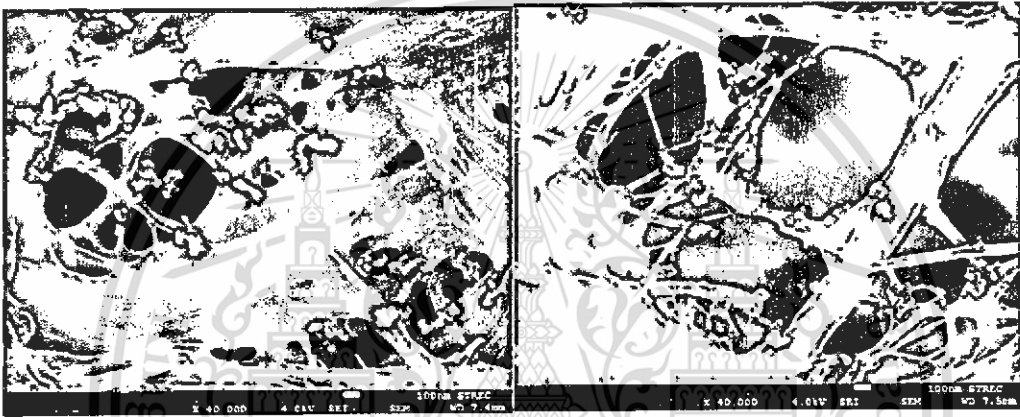
(g) 60%-2000

(s) 60%-2000



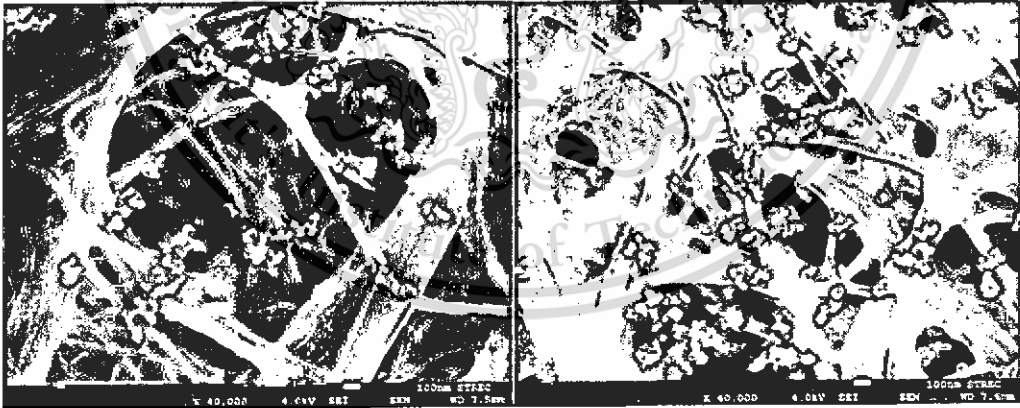
(h) 80%-2000

(t) 80%-2000



(i) 40%-2400

(u) 40%-2400



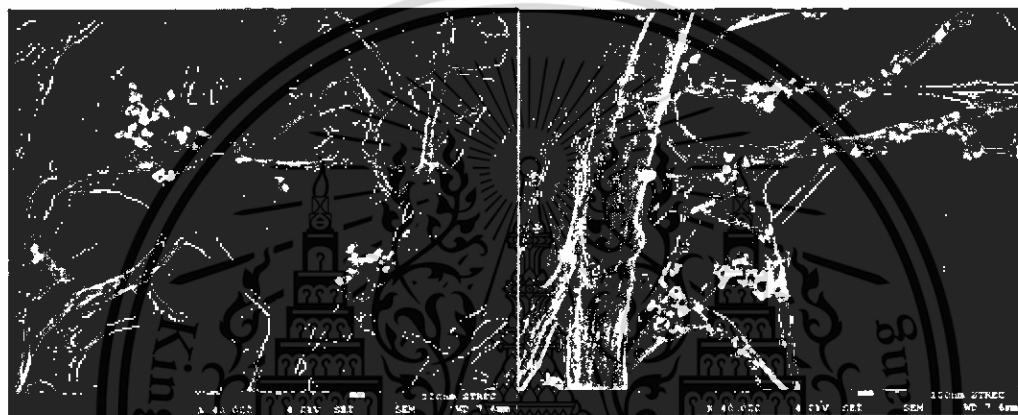
(j) 40%-2400

(v) 40%-2400



(k) 40%-2400

(w) 40%-2400



(l) 40%-2400

(x) 40%-2400

Figure 4.3 Particulate matter image of (a)-(l) diesel and (m)-(x) biodiesel in various conditions by scanning electron microscope

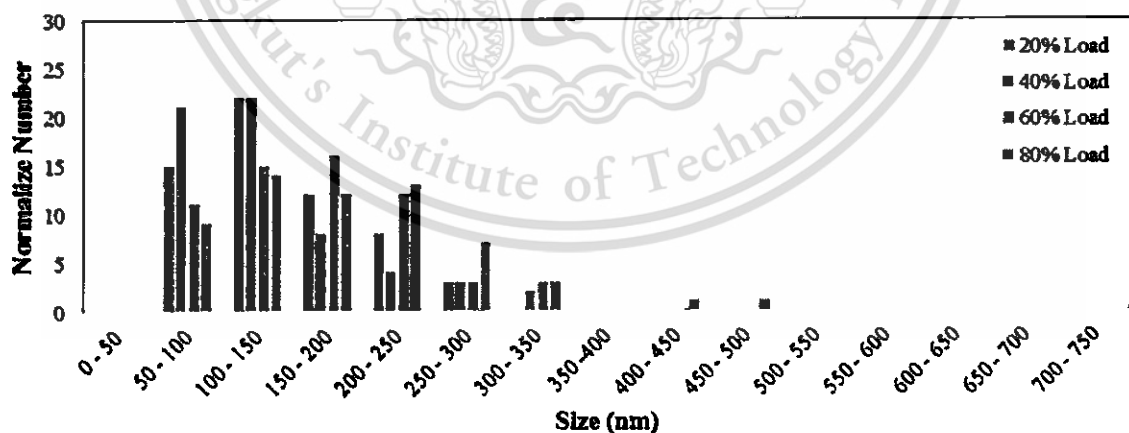
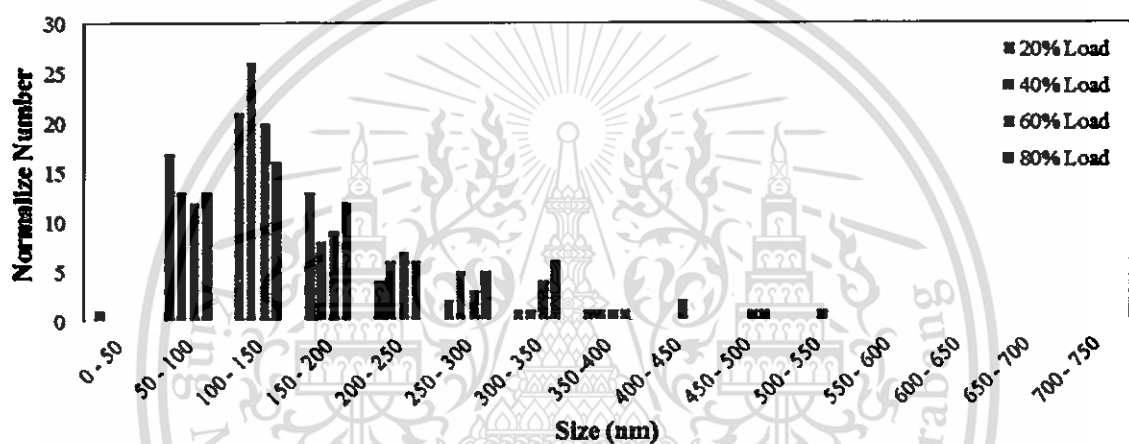
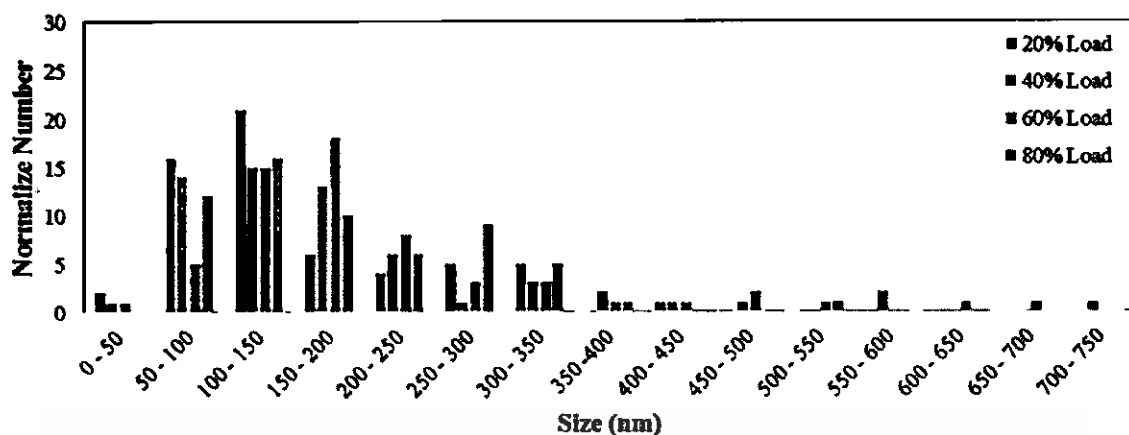
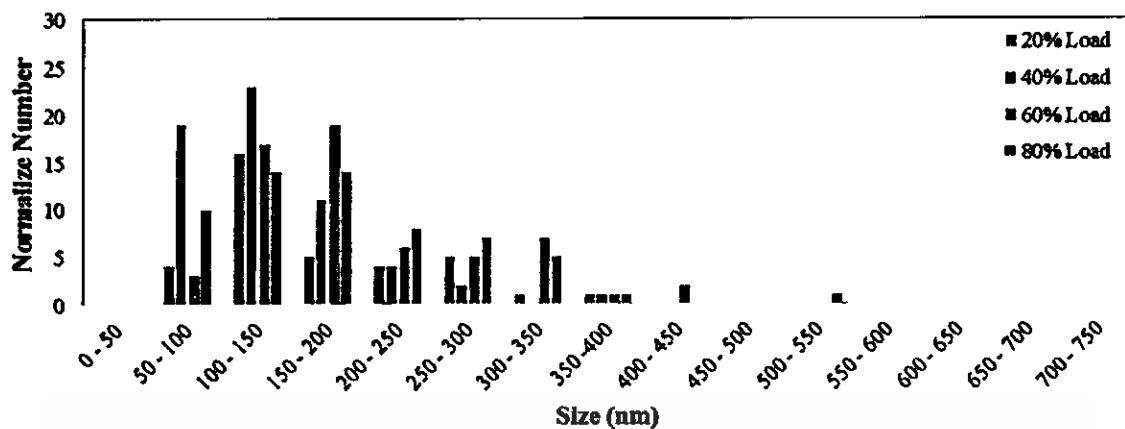


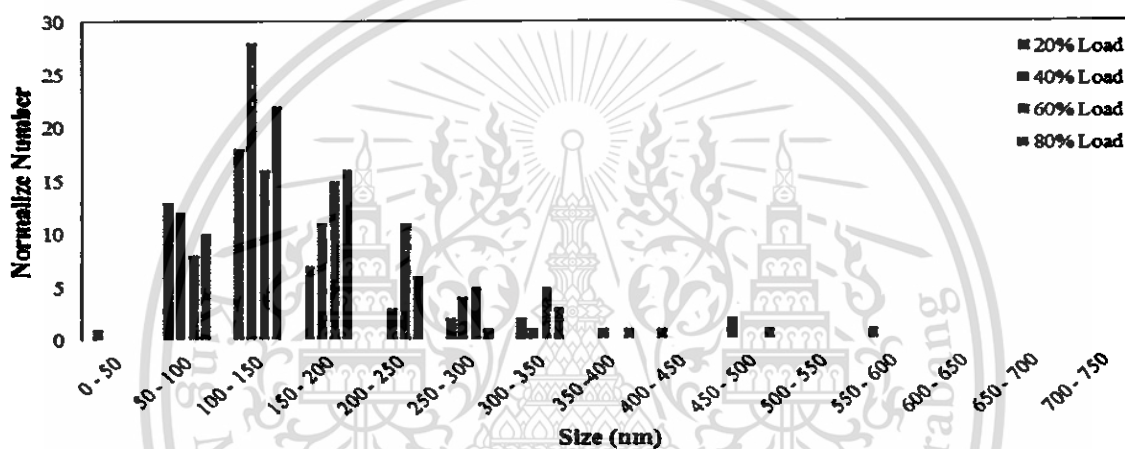
Figure 4.4 Size distribution of agglomerate particulate matter from diesel at the engine operation conditions are 20, 40, 60 and 80% of engine load and (a) 1600, (b) 2000 and (c) 2400 rpm of engine speed, respectively

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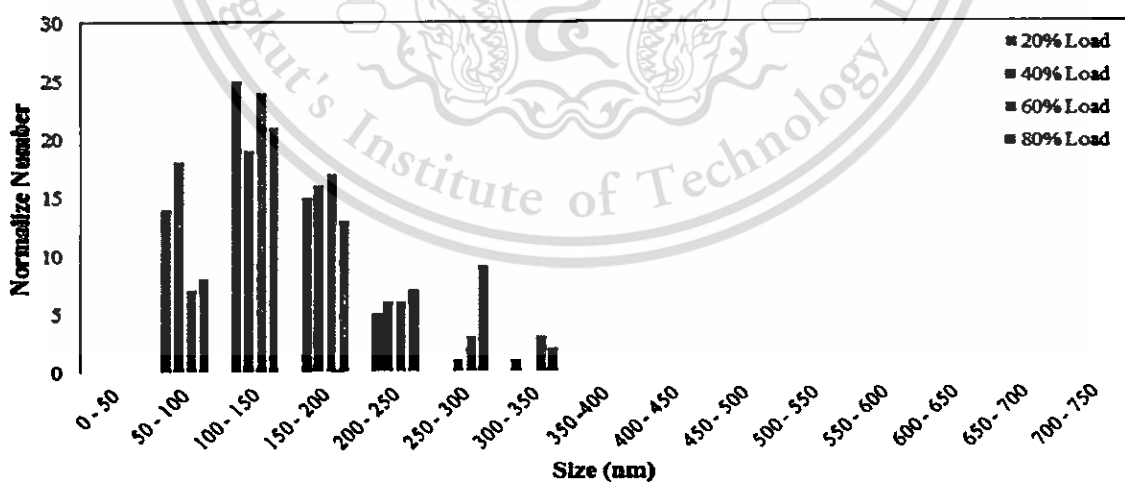
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(a) Biodiesel Engine 1600 rpm



(b) Biodiesel Engine 2000 rpm



(c) Biodiesel Engine 2400 rpm

Figure 4.5 Size distribution of agglomerate particulate matter from biodiesel at the engine operation conditions are 20, 40, 60 and 80% of engine load and (a) 1600, (b) 2000 and (c) 2400 rpm of engine speed, respectively

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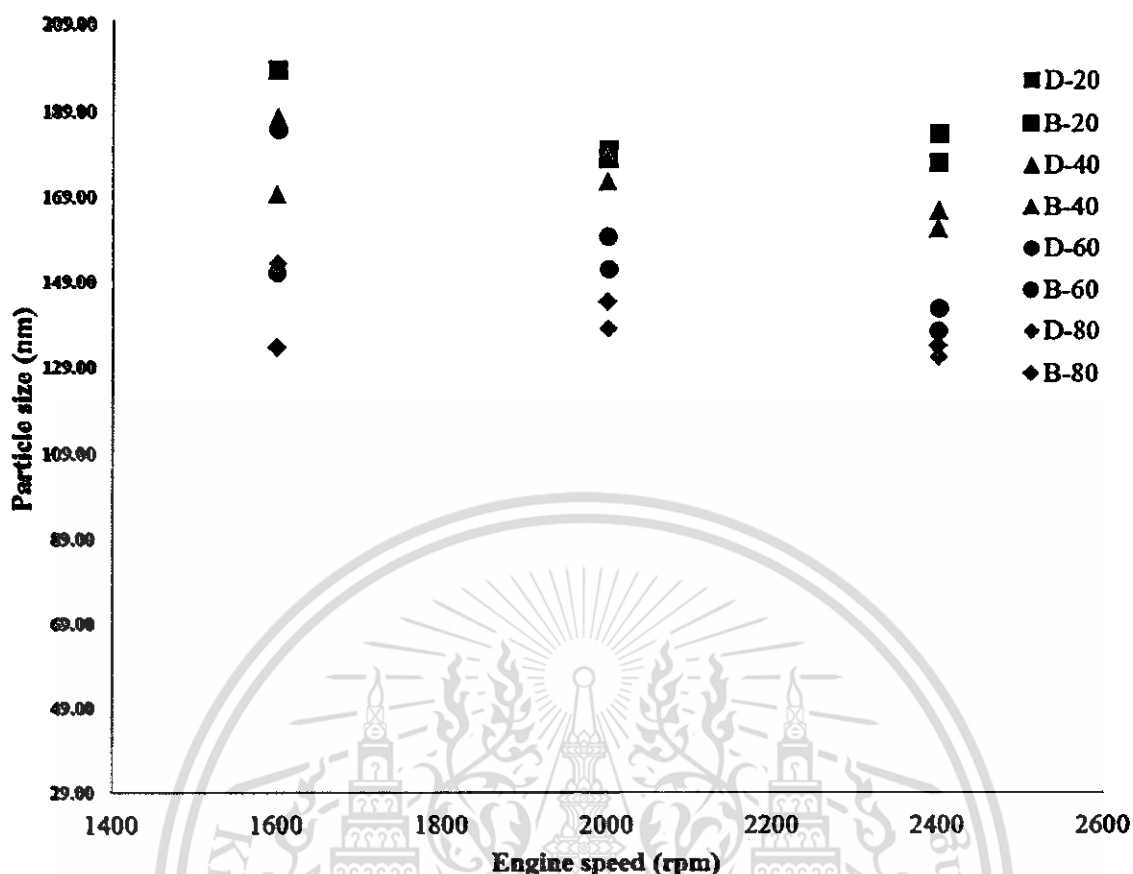


Figure 4.6 Average size distribution of agglomerate particulate matter from diesel versus biodiesel under 20, 40, 60 and 80% of engine load and 1600, 2000 and 2400 rpm of engine speed using SEM image processing method

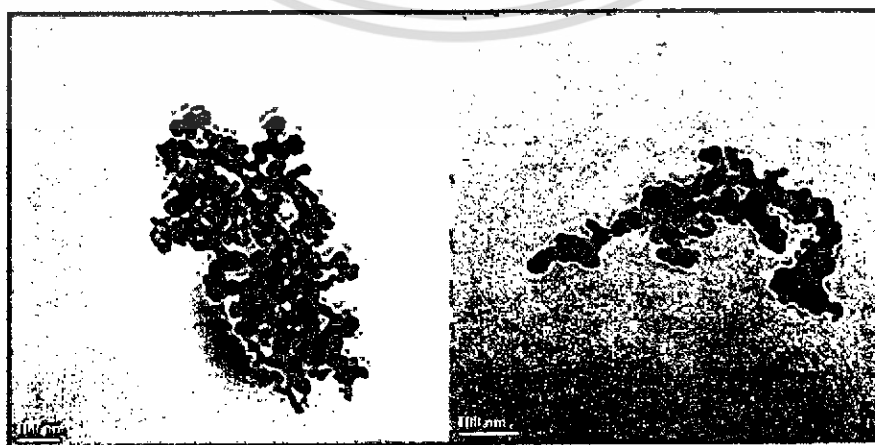
4.1.3.2 Single size

The particulate matter powder collected from exhaust gas of diesel and biodiesel combustion was taken image by transmission electron microscope. An approximately 100 particles was measured by average of two diagonal lengths to verified primary particle size distribution. Figure 4.7 shows particulate matter image from scanning electron microscope in various conditions. A particulate matter size distribution in primary mode of diesel and biodiesel at engine speed 1600 rpm, 2000 rpm and 2400 rpm are shown in Figure 4.8 and 4.9 respectively. The result of measuring particle sizes is in the range of 10-60 nm. It was clearly observed much amount of particle diameters are in the range of 30-40. Figure 4.10 shows Average size distribution of Primary particle particulate matter from diesel at versus

biodiesel under 20, 40, 60 and 80% of engine load and 1600, 2000 and 2400 rpm of engine speed particle diameter size decreased when increasing engine speed for both of diesel and biodiesel particulate matter. The exhaust gas temperature also gradually increased when increasing engine speed. It means particulate matter oxidation rate inside combustion chamber increased when increasing engine speed (increasing temperature) due to lower heat loss on cylinder surface compare to lower engine speed. Similarly, particle diameter size decreased when increasing engine load for both of diesel and biodiesel particulate matter. A primary particulate matter in high load condition might be oxidized around the particle surface because the temperature in combustion chamber and exhaust gas of high load condition is higher than that low load condition.

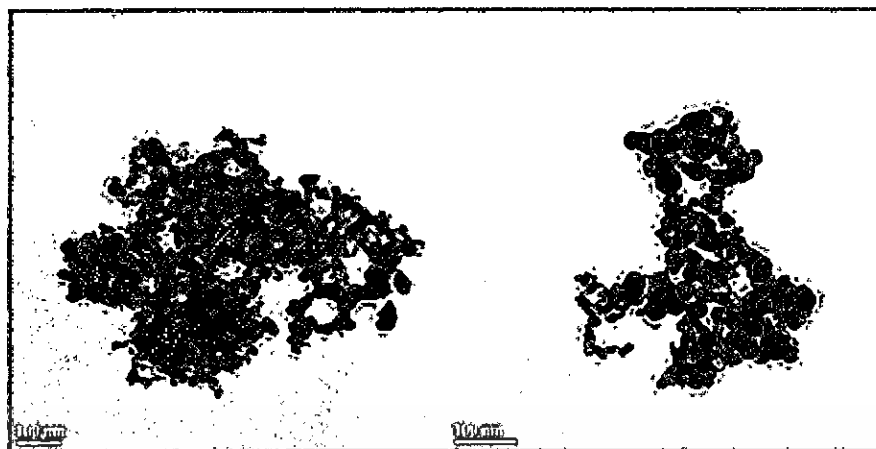
When focus on the effect of biodiesel fuel, the particulate matter from biodiesel combustion is emitted smaller size than that of diesel combustion. Due to the oxygenate biodiesel fuel include more available oxygen which is readily oxidized with particulate matter in combustion flame. This cause results smaller primary particulate matter of biodiesel is emitted to atmosphere.

In this thesis, the transmission electron microscope image was used to determine the primary size distribution of the diesel and biodiesel particulate matter. These images were measured by average of two diagonal of the particle in measurement program. It might be the fallibility from the uncertainly of measurement technique such as the unclear image from the transmission electron microscope and the accuracy of measurement technique. These reasons cause to not too much different on size distribution of the diesel and biodiesel primary particulate matter.



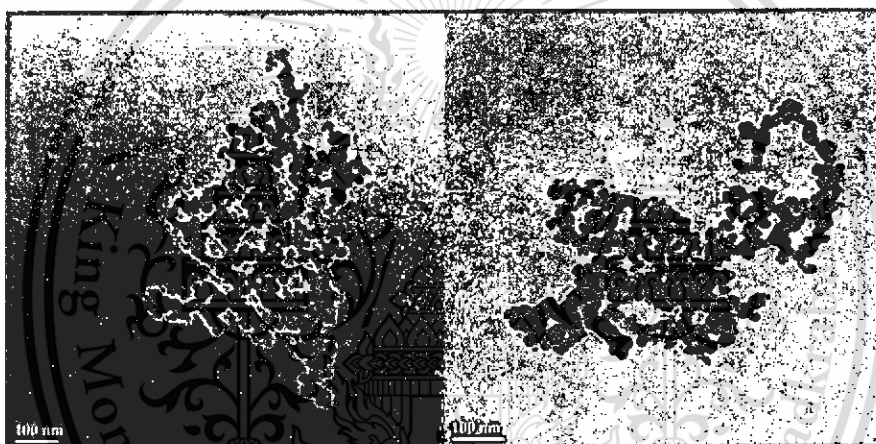
(a) 20%-1600

(m) 20%-1600



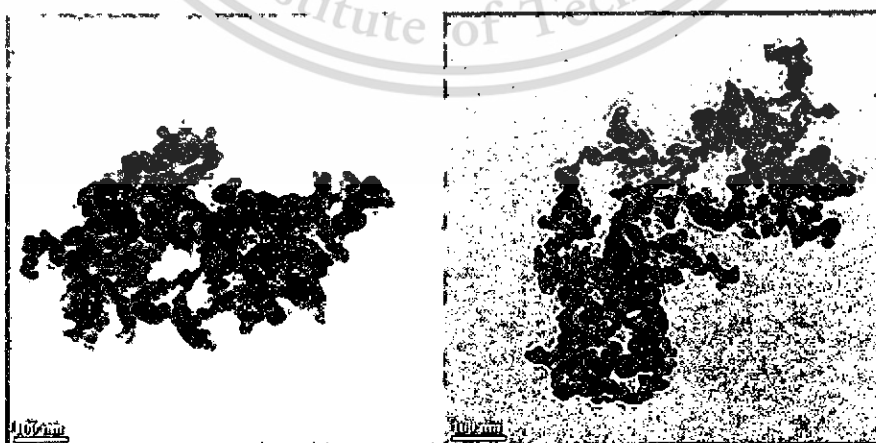
(b) 40%1600

(n) 40%1600



(c) 60%-1600

(o) 60%-1600

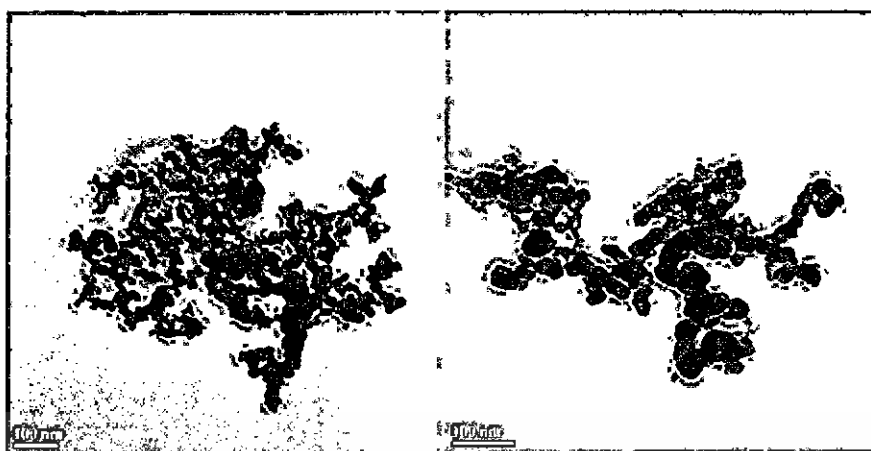


(d) 80%-1606

(p) 80%-1600

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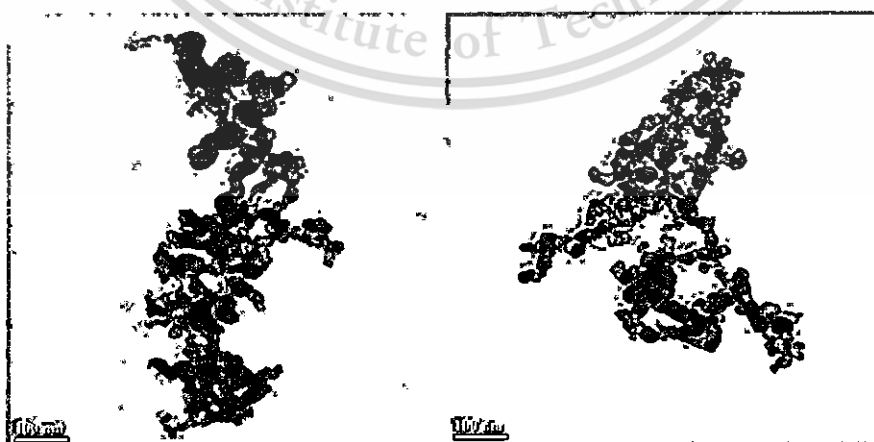
(e) 20%-2000

(q) 20%-2000



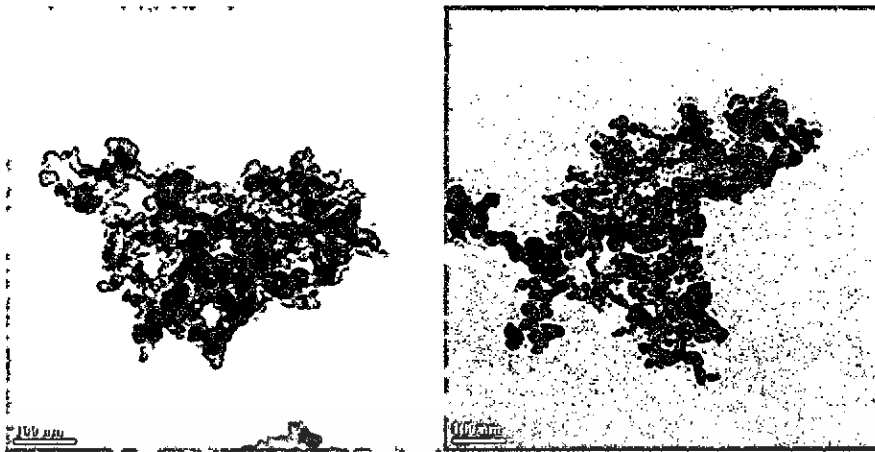
(f) 40%-2000

(r) 40%-2000



(g) 60%-2000

(s) 60%-2000



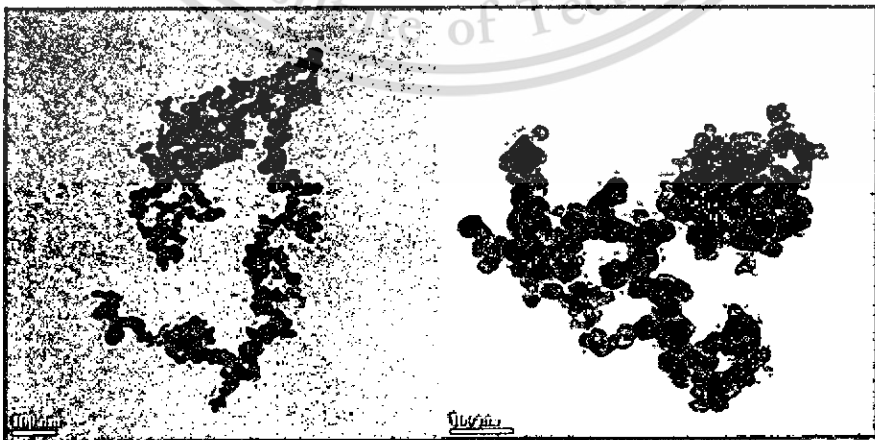
(h) 80%-2000

(t) 80%-2000



(i) 40%-2400

(u) 40%-2400



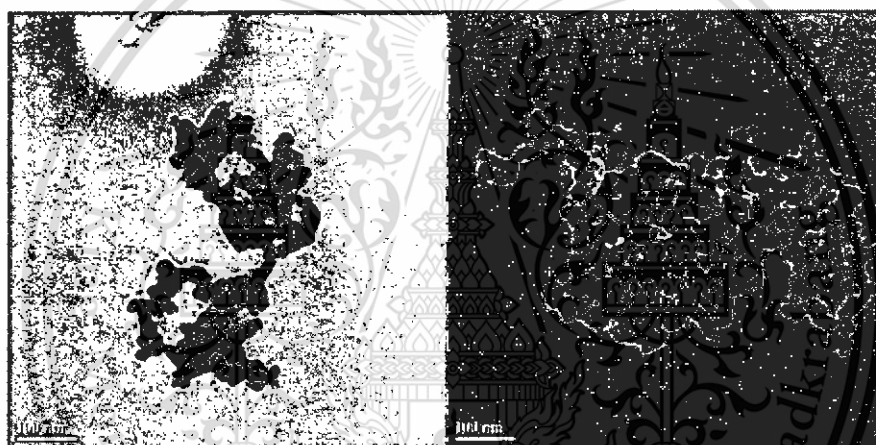
(j) 40%-2400

(v) 40%-2400



(k) 40%-2400

(w) 40%-2400

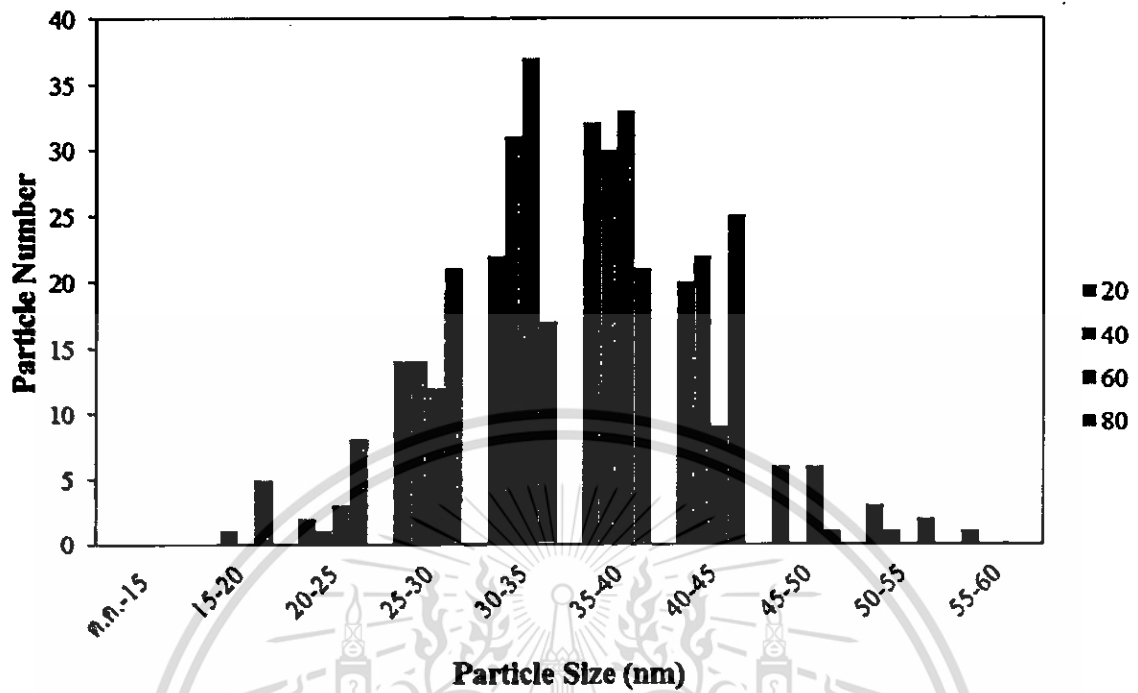


(l) 40%-2400

(x) 40%-2400

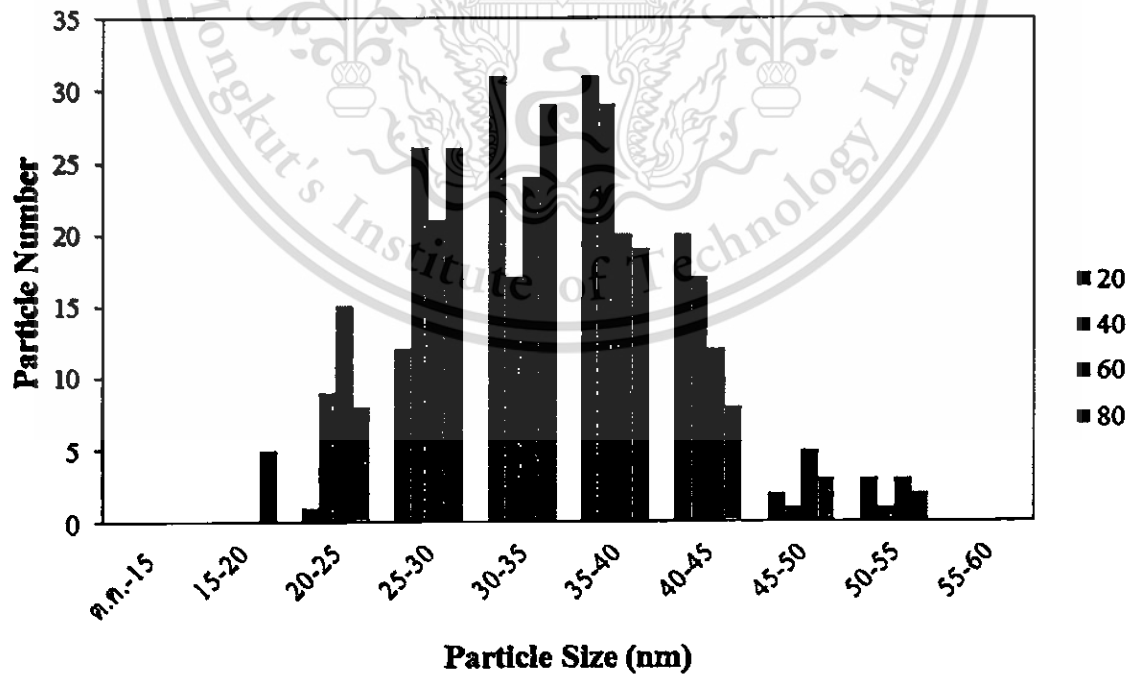
Figure 4.7 Particulate matter image of (a)-(l) diesel and (m)-(x) biodiesel in various conditions by transmission electron microscope

Diesel 1600RPM



(a)

Diesel 2000RPM



(b)

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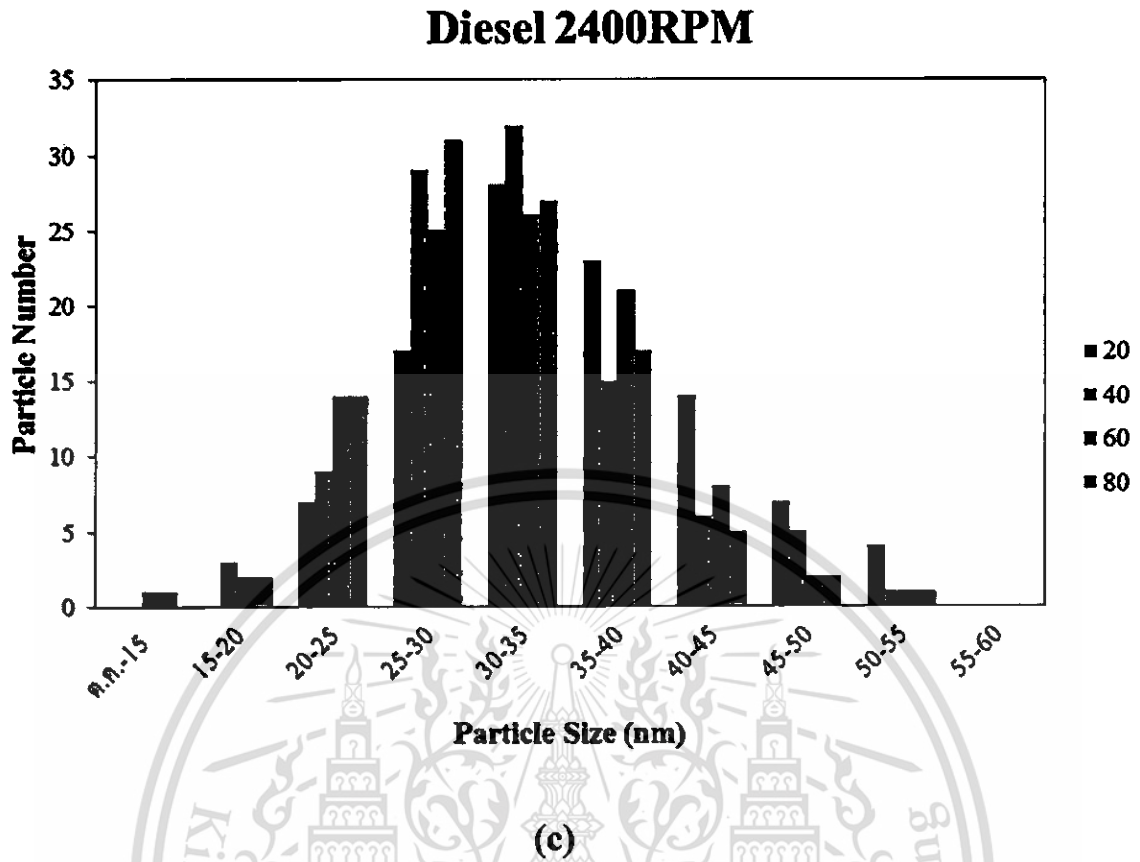
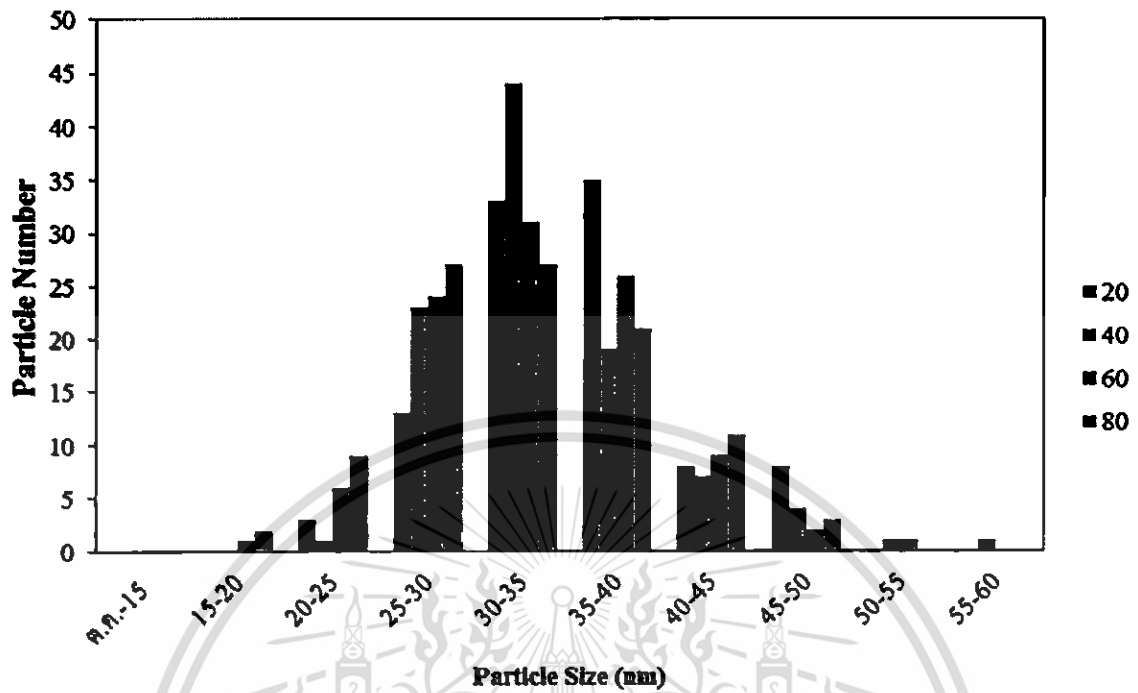


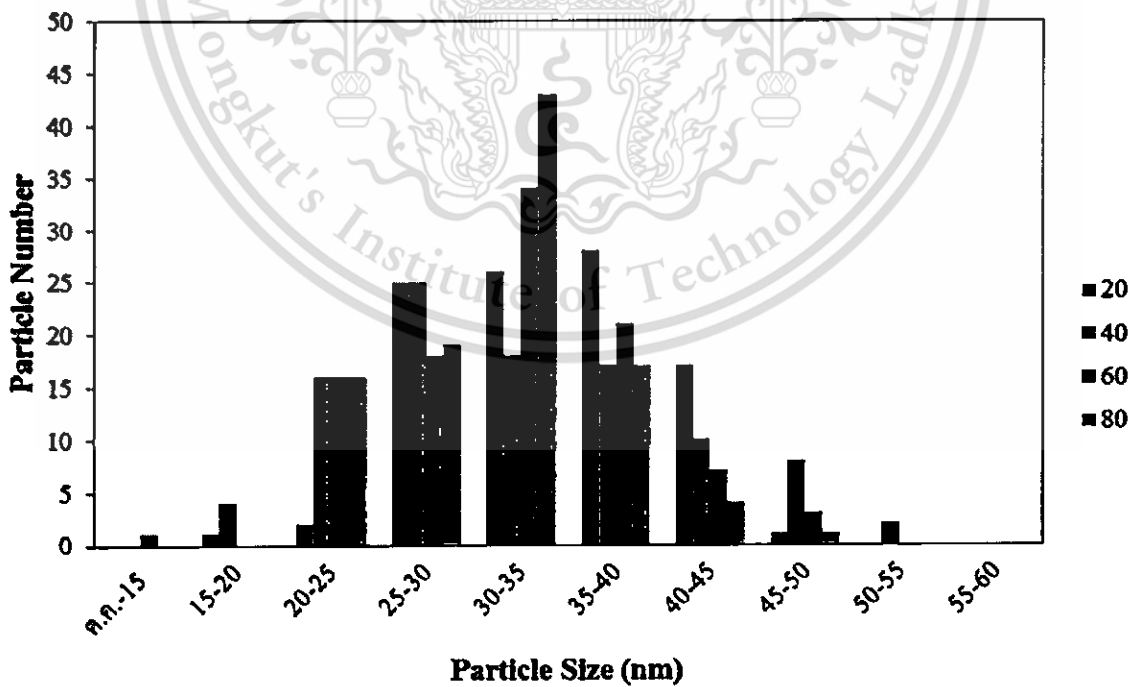
Figure 4.8 Size distribution of primary particulate matter from diesel at the engine operation conditions are 20, 40, 60 and 80% of engine load and (a) 1600, (b) 2000 and (c) 2400 rpm of engine speed, respectively

Biodiesel 1600RPM



(a)

Biodiesel 2000RPM



(b)

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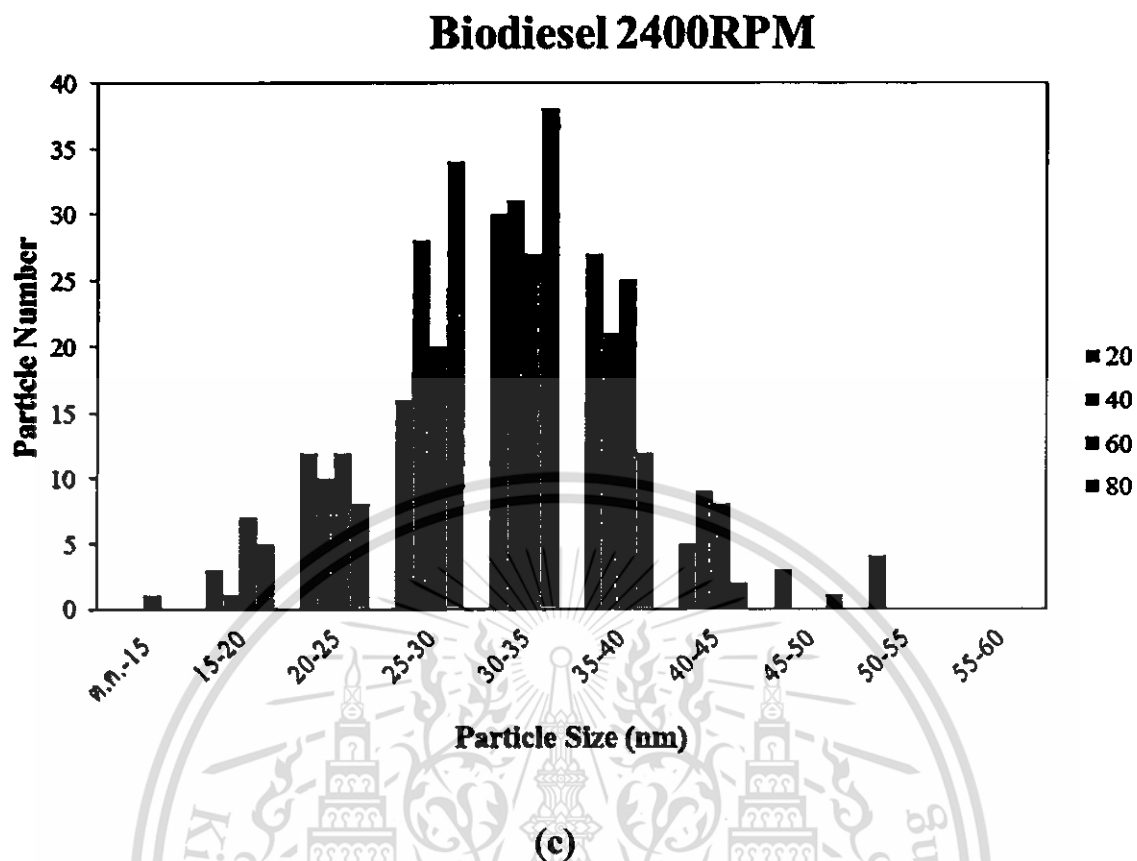


Figure 4.9 Size distribution of primary particulate matter from Biodiesel at the engine operation conditions are 20, 40, 60 and 80% of engine load and (a) 1600, (b) 2000 and (c) 2400 rpm of engine speed, respectively

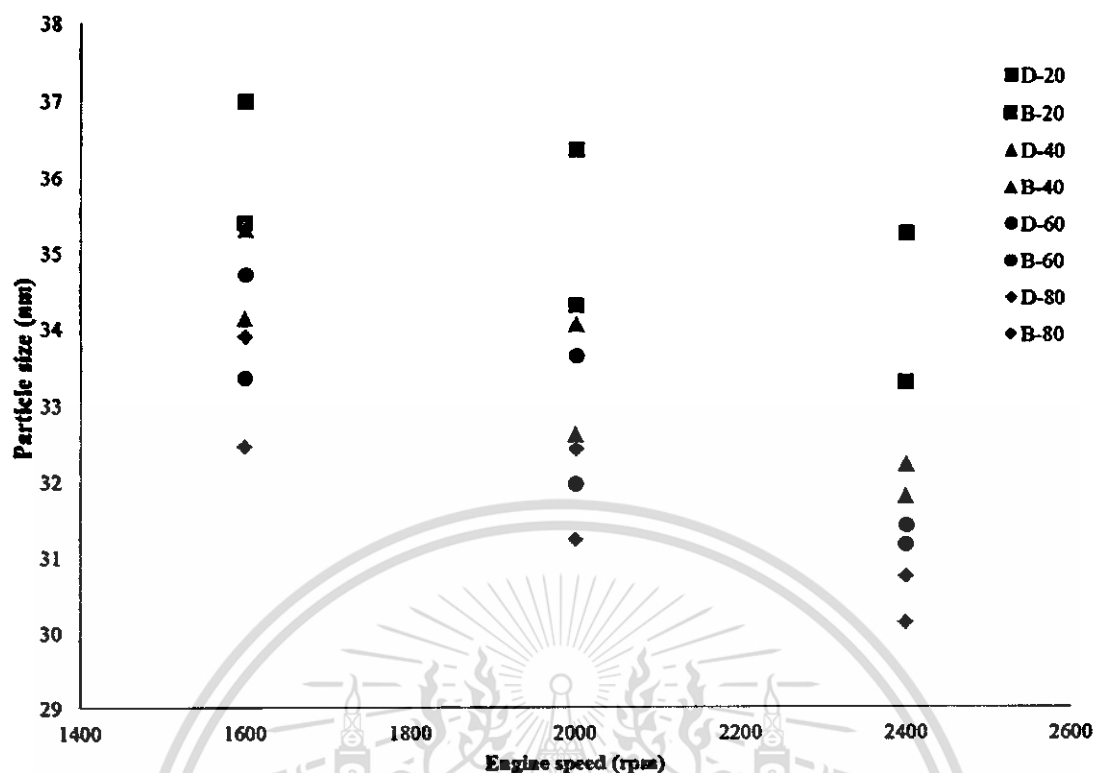


Figure 4.10 Average size distribution of primary particulate matter from diesel versus biodiesel under 20, 40, 60 and 80% of engine load and 1600, 2000 and 2400 rpm of engine speed using SEM image processing method

4.1.4 Trapping mechanism

The exhaust gas of diesel and biodiesel engine is flowed through the 25.4 mm x 25.4 mm x 0.5 mm of conventional diesel particulate filter for trapping particulate matter from incomplete combustion. The trapping behavior on diesel and biodiesel particulate matter is compared in trapping process by differential pressure in inlet and outlet of filter (pressure drop) at constant temperature 200 °C. Moreover, the smoke meter analyzes for trapping efficiency of filter and show the result on black smoke percentage after DPF during filter.

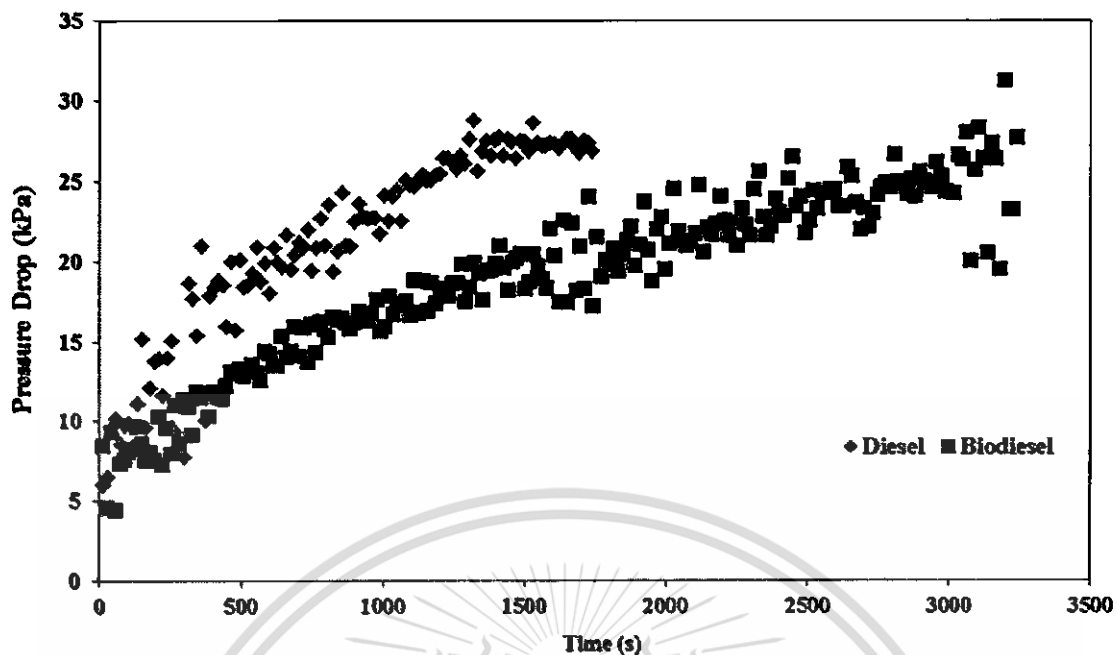


Figure 4.11 Pressure drop in particulate filter trapping

Figure 4.11 shows the particulate matter from diesel and biodiesel trapping in the conventional diesel particulate filter. The trapping duration of diesel particulate matter was approximately 1600 second. While the trapping duration of biodiesel particulate matter was approximately 3200 second, slower than that of the diesel particulate filter. The biodiesel particulate matter uses more time duration to trap full the diesel particulate filter when compare to the diesel particulate matter. The biodiesel particulate matter was emitted lower than that the diesel particulate matter. The pressure during the biodiesel particulate matter trapping in the filter was increased slower than the diesel particulate matter.

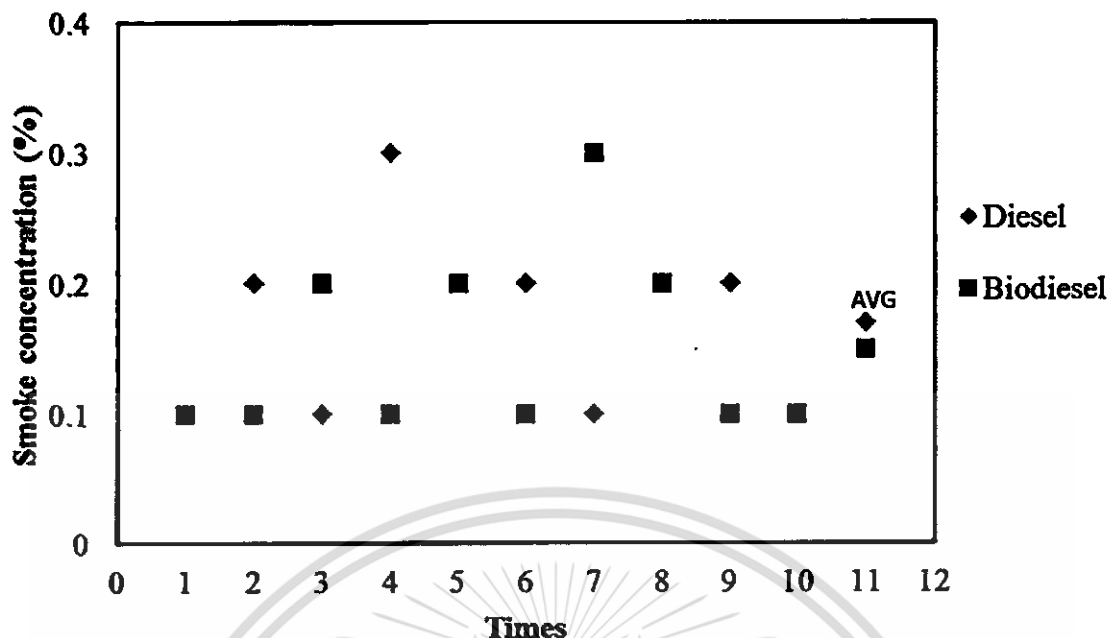


Figure 4.12 Black smoke concentration of particulate matter after DPF during trapping process

The particulate matter was trapped after DPF by the smoke meter during trapping process. The particulate matter from diesel and biodiesel combustion was trapped on filter with the same concentration as shown in figure 4.12. The black smoke percentage confirms that the diesel and biodiesel particulate matter were trapped on DPF in the same behavior.

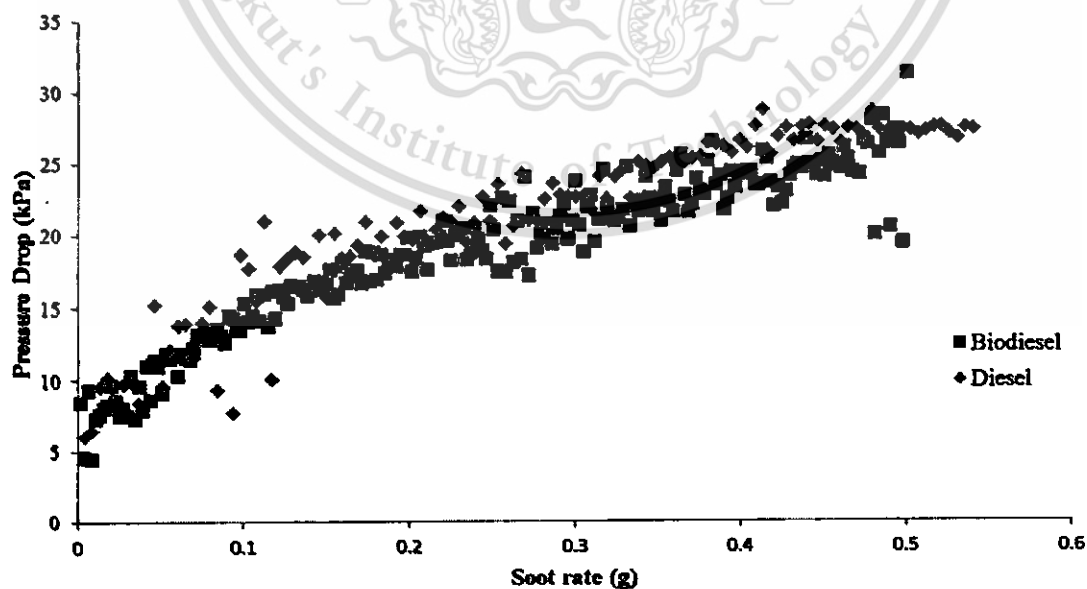


Figure 4.13 amounts of particulate matter were trapped on the DPF

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Figure 4.13 shows the amounts of particulate matter were trapped on the DPF with the difference pressure by calculate from the result of particulate matter flow rate. The quantities of diesel and biodiesel particulate matter that collected on PDF have the same mass. That can confirm the mass pf PM which trapped on DPF

From previous result can predict the trapping heavier of particulate matter on DPF as shown in figure 4.14. In the slope at the first state of graph shows the depth filtration behavior of particulate matter, the second state shows the soot cake filtration behavior. This result accord with conceptual model of pressure drop during particulate trapping.

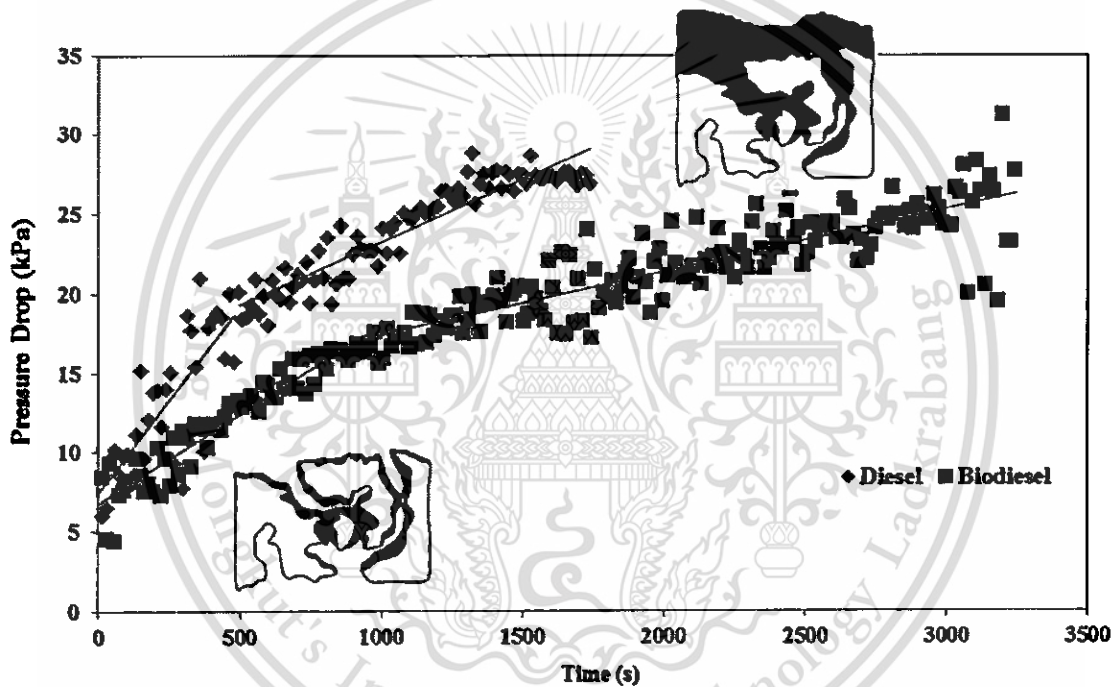


Figure 4.14 amounts of particulate matter were trapped on the DPF

4.2 Chemical characteristic

4.2.1 Oxidation kinetic

4.2.1.1 Mass conversion

The particulate matter from diesel and biodiesel combustion that mixed with DPF powder is investigated for oxidation kinetic by thermogravimetric analysis (TGA) method. The diesel and biodiesel particulate matter generated by engine operation at 80% load 2400rpm oxidation compare with carbon N - 330.

The particulate matter from diesel and biodiesel fuel was analyzed by TGA method to investigate for oxidation behavior of the particulate matter from diesel and biodiesel engine. The results from the TGA method are shown the mass conversion in figure. 4.15. The carbon black N - 330 was analyzed to be a base of pure carbon oxidation in this thesis. The graphs can be divided into two main parts, non-isothermal and isothermal. The non-isothermal part starts from the initiation of the experiment until reaching the desired temperature. At this phase, only nitrogen is used and there is not any oxidant, so the only change in mass of the particulate matter sample is due to vaporization of moisture and unburned hydrocarbon. The difference in conversion percentage and amount of it is affected by the heating time and the elemental compositions of the particulate matter samples from diesel and biodiesel. As isothermal stage begins, the air is introduced the mass conversion changes to mass oxidation and the mass percentage reduces as time passes. The oxidation becomes more complete for both Particulate matter samples as temperature increases and at 550 and 600 °C all particulate matter samples are burnt. For both of particulate matter, the increasing of temperature results in increase of mass conversion due to presence of more thermal energy for oxidation process. In comparison between the particulate matter samples, biodiesel shows faster percentage of conversion in comparison with diesel in all temperatures.

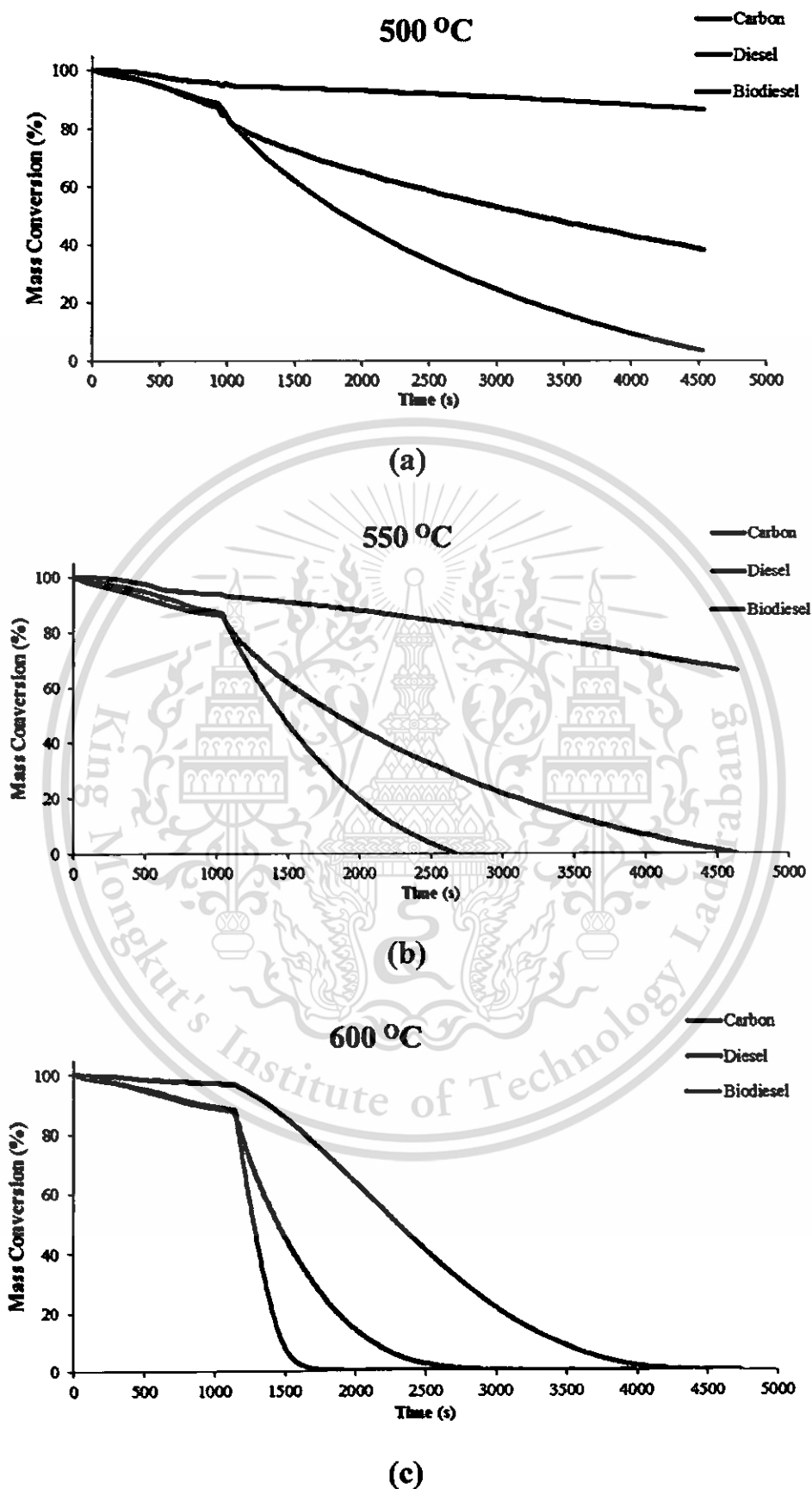


Figure 4.15 Mass conversion of diesel and biodiesel particulate matter at (a) 500 °C, (b) 550 °C and (c) 600 °C

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Then Chemical kinetics of TGA results was analyzed by relations below:



The chemical reaction rate in eq.1 can calculate from the TGA curve based on the chemical kinetic in eq.4.2.

$$-\frac{d[PM]}{dt} = k[PM]^n [O_2]^m \quad (4.2)$$

From eq.4.2 the reaction order (n) of particulate matter can be calculated by eq.4.3.

$$\ln\left[-\frac{d[PM]}{dt}\right] = n \ln[PM] + \ln[k * [O_2]^m] \quad (4.3)$$

Where PM is particulate matter mass, t is time, k is specific rate constant, m, n are the reaction order. The dependence of the specific rate constant k is expressed by eq.4.4.

$$k = A e^{-E_a/RT} \quad (4.4)$$

Where A is the frequency factor, E_a is the activation energy, R is the gas constant. The apparent activation energy can be calculated by eq.4.5 and

$$\ln\left[-\frac{1}{[C]^n} \frac{d[PM]}{dt}\right] = \frac{-E_a}{RT} + \ln[A * [O_2]^m] \quad (4.5)$$

4.2.1.2 Reaction order of particulate matter (n)

From the rate formula (eq.4.3) is used to solve the reaction order of diesel and biodiesel particulate matter and the results are shown and figure 4.16 and the results are presented in table 4.1.

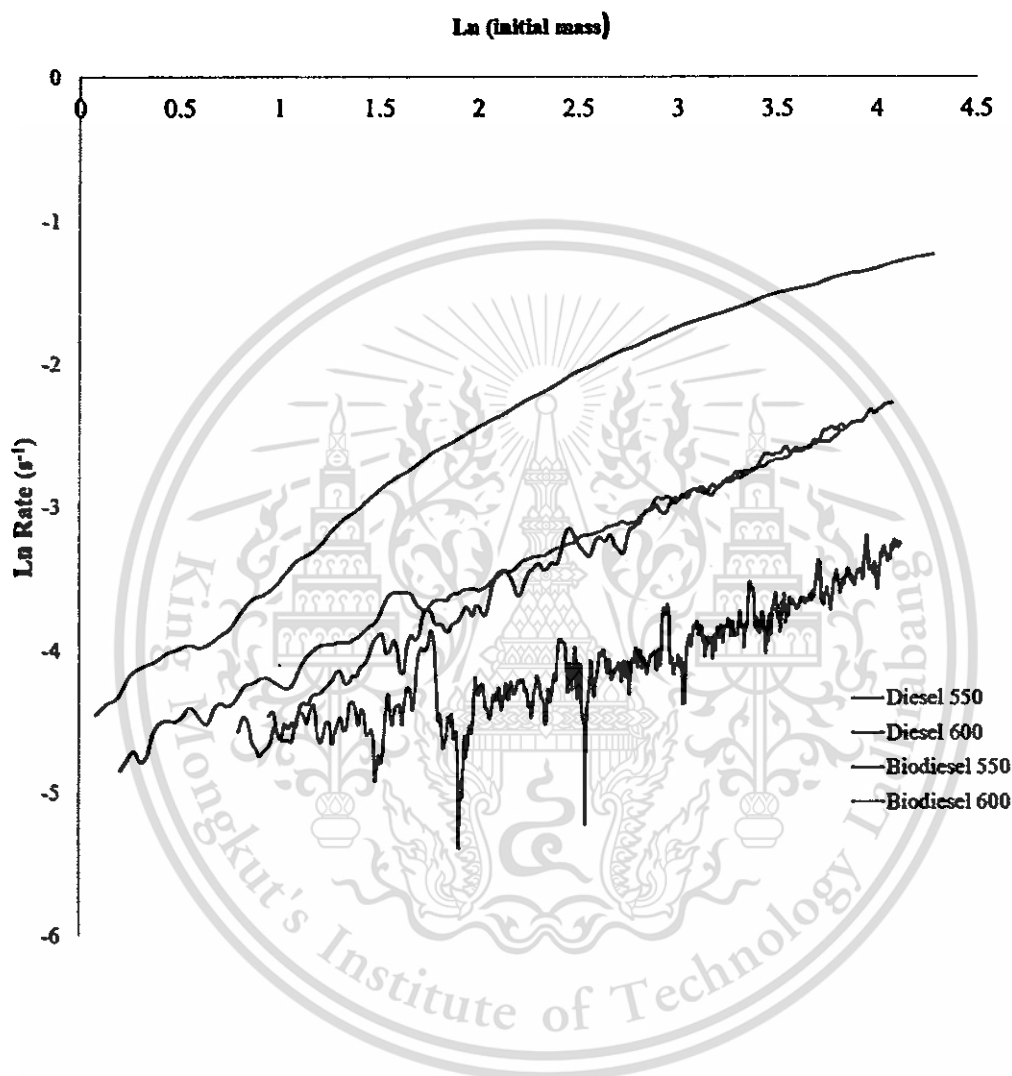


Figure 4.16 Particulate matter reaction order (n) for diesel and biodiesel particle in TGA

Table 4.1 The results of carbon reaction order

Particulate Matter Sample	n value
Diesel 550 °C	0.44
Diesel 600 °C	0.70
Biodiesel 550 °C	0.60
Biodiesel 600 °C	0.74

According to table 4.1, for both TGA condition biodiesel has higher n value in comparison with diesel particulate matter and thus it shows better reactivity. None of the samples meet the shrinking core value (2/3) and it can be claimed that the particulate matter particles do not have a complete spherical shape.

4.2.1.3 Activation Energy (Ea)

Activation energy (Ea) is the minimum energy which is required to initiate and complete a chemical reaction. The lower activation energy means the better reactivity. At this study the, it's tried to divide the particulate matter mass conversion in three main groups and then the activation energy for each division is calculated. This can clarify the different compositions of particulate matter, VOF, SOF and SOL, by difference of activation energy value. The particulate matter conversion of all samples is divided to three parts, based on equal percentages of conversion rate of the samples including 20-40%, 40-60% and 60-80% burned. The activation energy of particulate matter samples at each division is calculated from Arrhenius graphs as shown in figure 4.17. The activation energy of first division (20-40%) is lower in comparison with the two remaining divisions. This can be due to presence of more VOF and SOF in the first stage of conversion, while in later stages most of SOF and VOF are consumed and most of the composition is SOL or carbonaceous, especially at last stage and therefore the higher values for activation energy can be seen in table 4.2. In comparison between diesel and biodiesel particulate matter samples, the activation energy of biodiesel is lower in all divisions and thus it can be a good reason for better reactivity of the biodiesel particulate matter hence lower activation energy is indication of easier oxidation at lower temperature.

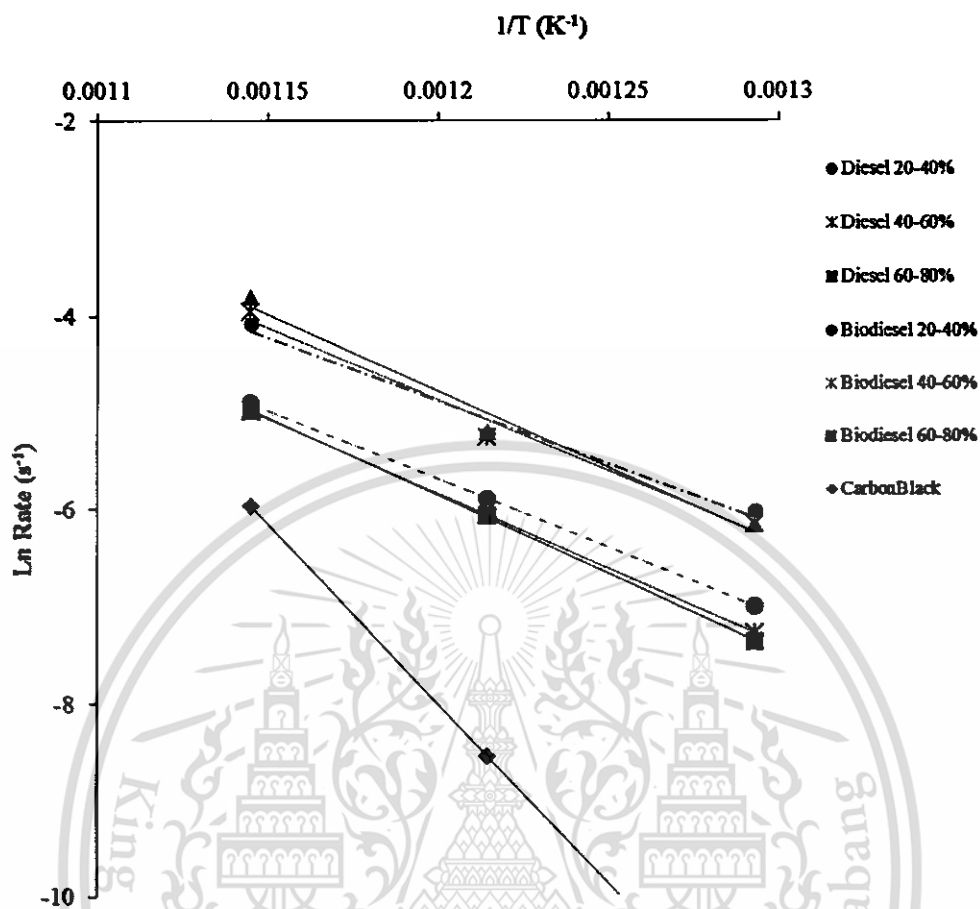


Figure 4.17 Arrhenius plots of carbon black, diesel and biodiesel particulate matter oxidation on conventional cordierite DPF powders using TGA isothermal method, 500-550-600 °C

Table 4.2 Calculated apparent activation energies (E_a) of particulate matter oxidize on conventional cordierite DPF powder

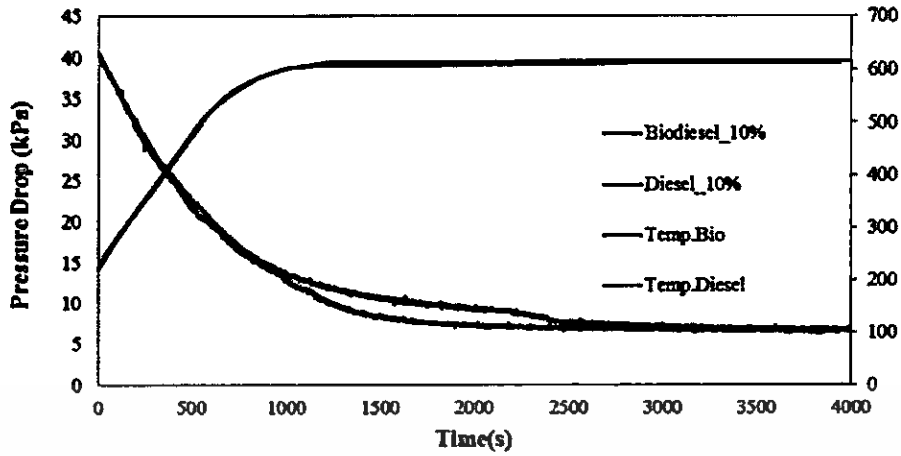
Particulate Matters burned fraction	Apparent activation energy E_a (kJ/mole)
Diesel Engine's PMs	124±7
Diesel 20-40% burned	117
Diesel 40-60% burned	124
Diesel 60-80% burned	130
Biodiesel Engine's PMs	121±11
Biodiesel 20-40% burned	109
Biodiesel 40-60% burned	121
Biodiesel 60-80% burned	131
Carbon Black 20-40%	178

4.2.2 Regeneration mechanism

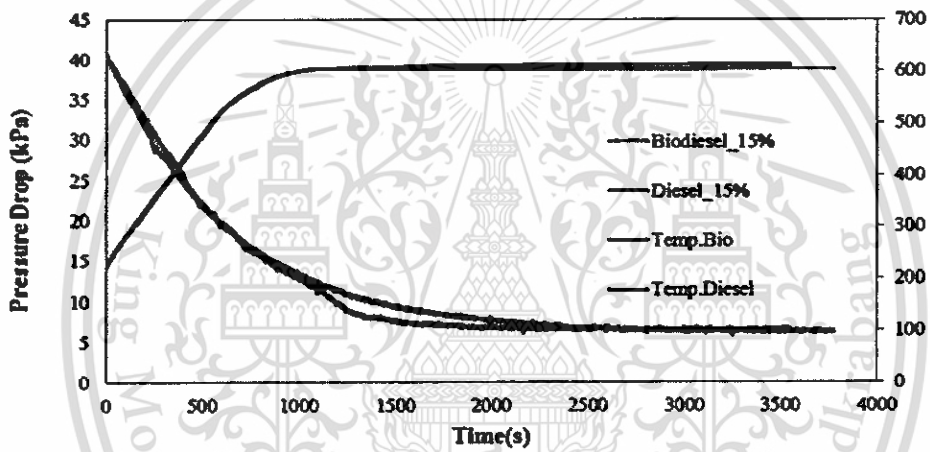
The regeneration behavior on DPF of diesel and biodiesel particulate matter is compared in regeneration process by differential pressure in inlet and outlet of DPF (pressure drop). The regeneration process is done with the high temperature tube furnace. The temperature in regeneration process was increased from 200 to 600 °C and operate with 10 15 and 21% of oxygen gas. In regeneration process can be divided into two main parts, non-isothermal and isothermal like a TGA analysis. The results in regeneration process as shown in figure 4.18. In the first state in all of conditions have only nitrogen is used and there is not any oxidant, the pressure drop in all of condition have the same trend due to vaporization of moisture and unburned hydrocarbon. In the second state, gas oxygen was released to the system to oxidize with PM. The pressure drop of regeneration process decrease as time passes that means the particulate matter on DPF was oxidize. The oxidation becomes more complete faster for both particulate matters as oxygen content increase due to presence of more oxygen for oxidation process. In comparison between the regeneration of biodiesel shows faster duration in comparison with diesel in pressure all of condition.

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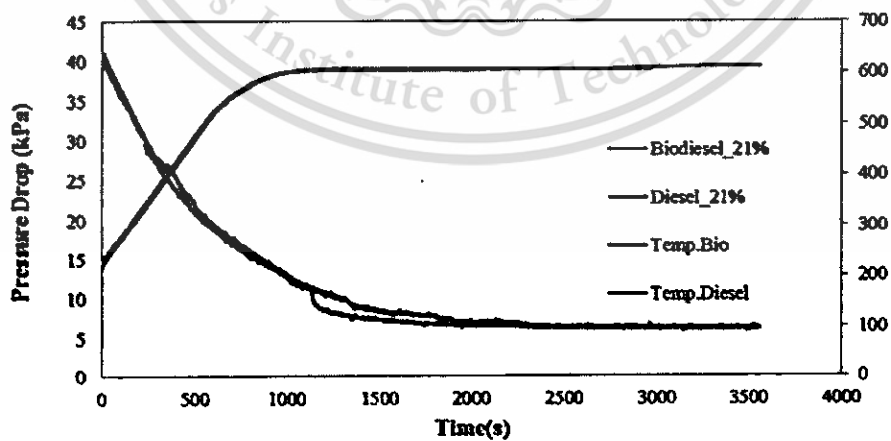
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(a)



(b)



(c)

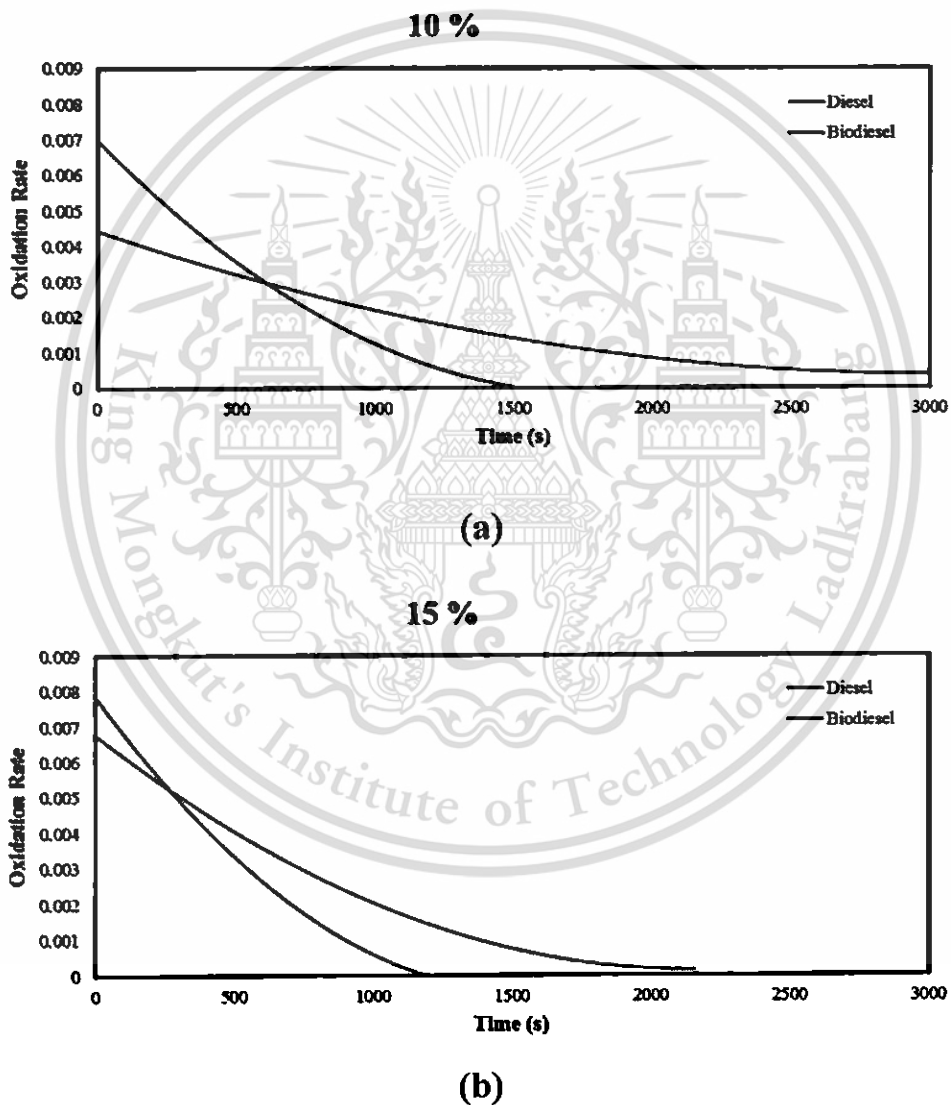
Figure 4.18 Pressure differential of regeneration process by using oxygen

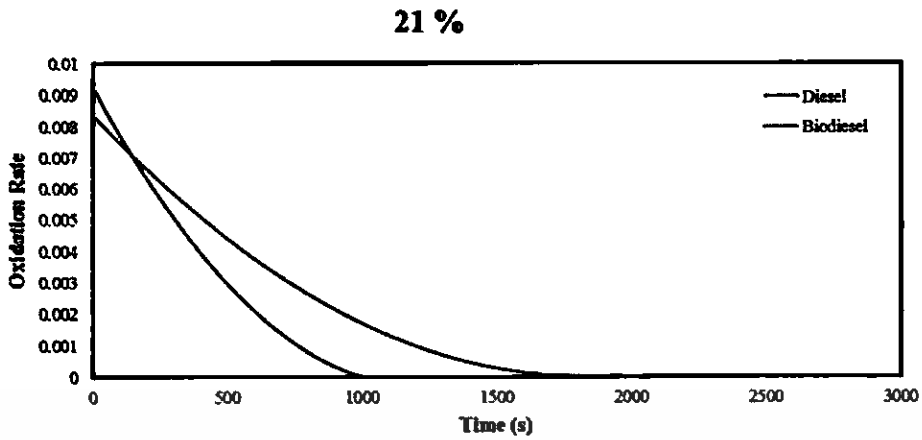
(a) 10%, (b) 15% and (c) 21%

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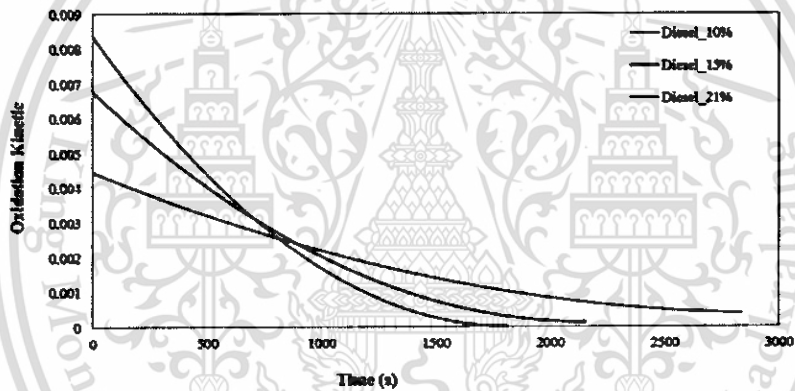
The oxidation kinetic of diesel and biodiesel particulate matter was calculated from the pressure drop results in regeneration process at the second state. The biodiesel particulate matter was oxidized faster than diesel particulate matter in all condition tests as shown in figure 4.19. This result accords with the activation energy of both particulate matters at 60-80% which calculated from TGA analysis. Figure 4.20 show the impact of oxygen content for particulate matter oxidation, the increasing of oxygen content was the increasing of particulate matter oxidation kinetic due to the reaction order of oxygen (m) was increase which follows from eq. 4.2.



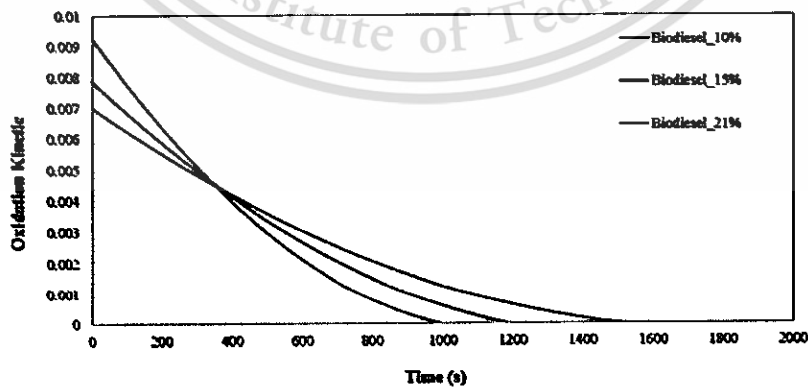


(c)

Figure 4.19 Oxidation kinetic of diesel and biodiesel particulate matter at (a) 10% (b) 15% and (c) 21% oxygen content



(a)



(b)

Figure 4.20 Oxidation kinetic of particulate matter with various oxygen content (a) diesel and (b) biodiesel

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Chapter 5

CONCLUSIONS

In this research, the particulate matter from diesel and biodiesel fuel combustion was investigated for physical and chemical characteristic to explain the trapping and regeneration behaviors of particulate matter on conventional diesel particulate filter.

- 5.1 Quantities of particulate matter in middle engine speed are lower than low and high engine speed because the middle engine speed is the condition of lowest engine energy consumption by the power at low engine speed loss from heat lost and the power at the high engine speed loss from friction lost.
- 5.2 Quantities of particulate matter increases when load increases because amount of fuel injection in combustion chamber is higher. That means more of fuel injection makes bigger rich zone in spray which affected to incomplete combustion.
- 5.3 Biodiesel fuel combustion produces particulate matters about half of that from diesel combustion because biodiesel fuel consisting of more oxygen atom in fuel molecule is readily oxidized with available oxygen in the flame zone.
- 5.4 The size of particulate matter in agglomerate and primary mode decreases when the load and speed increase. Due to the high temperature in combustion chamber and high temperature in exhaust gas is oxidized particulate matter while suspended in the combustion chamber and the exhaust gas.
- 5.5 The accumulate particle size of biodiesel particulate matter is smaller than the diesel particulate matter by diesel particle was around 140-190 nm and biodiesel particle was around 130-180 nm. Oxygen content in the biodiesel fuel promotes complete combustion. The completely combustion has lower amount of carbon atom. Then, the particulate matter from biodiesel has smaller size.

- 5.6 In this thesis, the particulate matter from both of diesel and biodiesel is not explicitly difference. It might be the fallibility from the uncertainly of measurement technique such as the unclear image from the transmission electron microscope and the accuracy of measurement technique. These reasons cause to not to different on size distribution of the diesel and biodiesel primary particulate matter. Actually, the particulate matter from biodiesel should be emitted in smaller size than that of the particulate matter from diesel for a primary particle. Due to the oxygenate biodiesel fuel include more available oxygen which is readily oxidized with particulate matter in combustion flame. This cause results smaller primary particulate matter of biodiesel is emitted to atmosphere.
- 5.7 The biodiesel particulate matter can be oxidized at apparent lower activation energy. Due to impact of unburned oxygenated fuel of biodiesel plays an important role in particulate matter combustion cause to lower apparent activation energy in biodiesel particulate matter oxidation.
- 5.8 Biodiesel particulate matter has higher reaction order value (0.67) than that of diesel (0.52). This can indicate that biodiesel particulate matter has a complete spherical form which is match with shrinking core value, 0.66. That means biodiesel particulate matter can be oxidizing faster than diesel particulate matter.
- 5.9 The conventional DPF can be used to trap both diesel and biodiesel particulate matter. Although, the biodiesel particulate matter is emitted in smaller particle size than the diesel PM. That mean, the particle size did not significantly affect DPF trapping process because the pore size of DPF is very large compared to the size of the particle emission.
- 5.10 The duration regeneration DPF which trapped biodiesel particulate matter is faster than that of diesel and it's alike to the oxidation rate of particulate matter samples in TGA. The smaller size and higher activation of the biodiesel particulate matter can be the main reasons for better oxidation.

The biodiesel fuel has many advantages. The biodiesel fuel is carbon neutral and can be produced in domestic from the palm oil etc. In addition, the using of biodiesel fuel instead of diesel fuel in the compression ignition engine without any modification can be also reduce the particulate matter

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concentration emit to the atmosphere around two times. Also the particulate matter size from biodiesel is smaller than that of the particulate matter from diesel. However, the conventional diesel particulate matter can be used to trap the smaller size of the biodiesel particulate matter efficiently. Moreover, the biodiesel particulate matter trapped in the particulate filter can be removed easier than that of the diesel particulate matter in regeneration process because of the higher unburned HC and easily oxidized of the biodiesel particulate matter than the diesel particulate matter.



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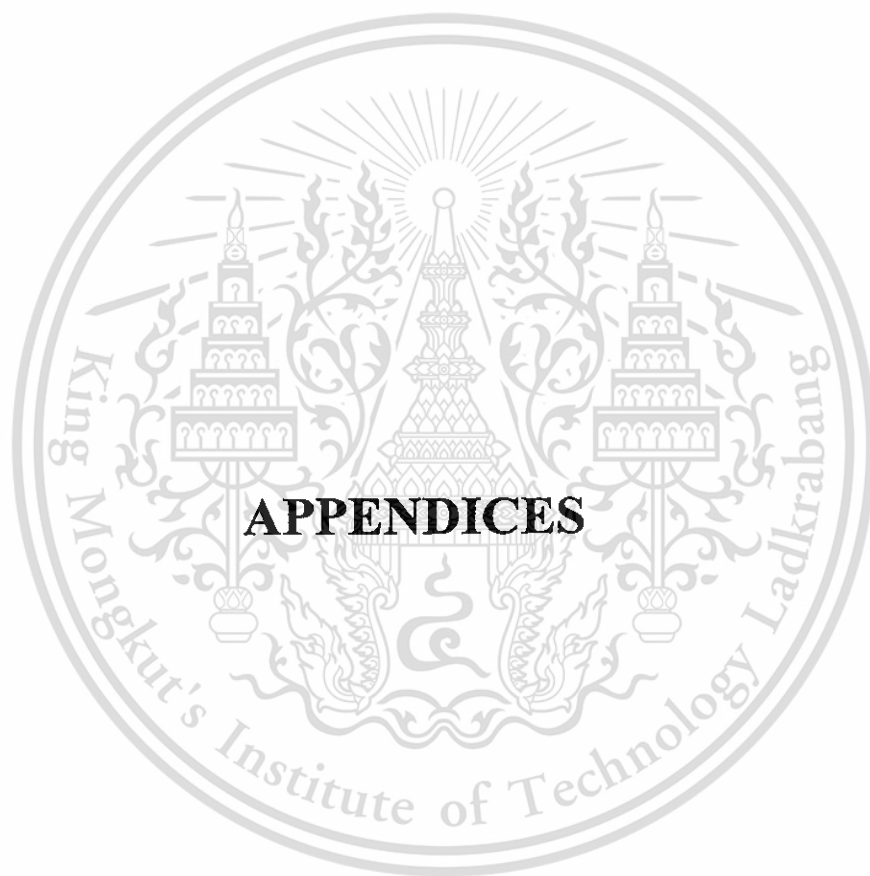
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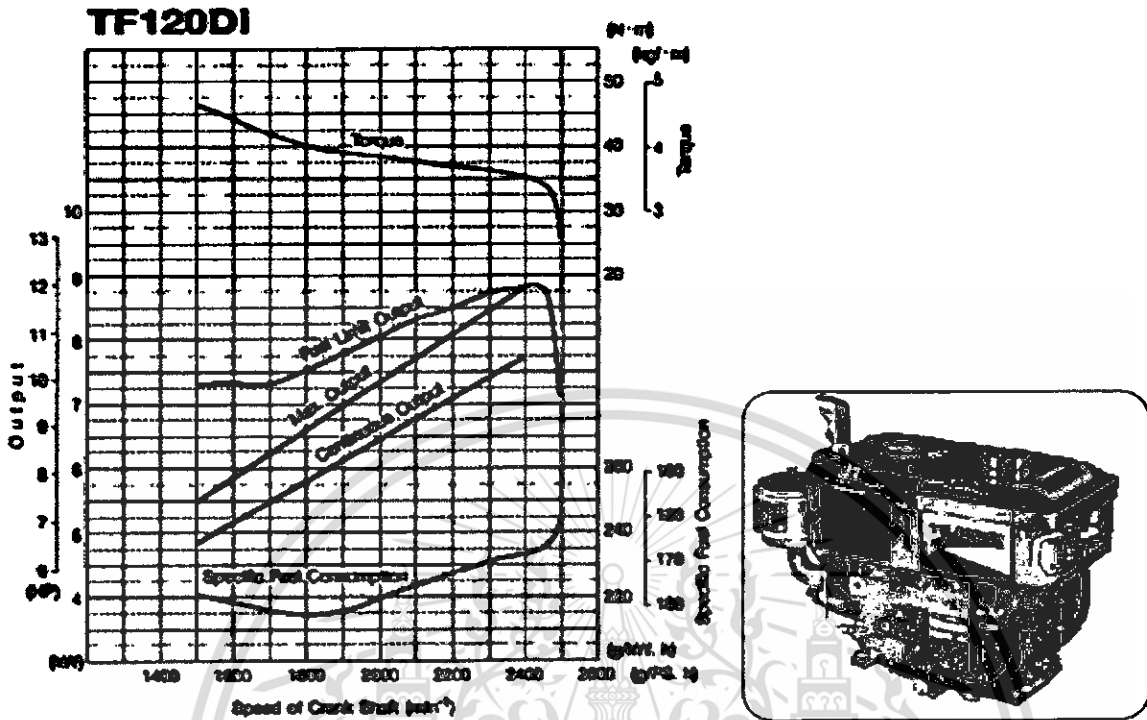
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A-1: Diesel engine specification



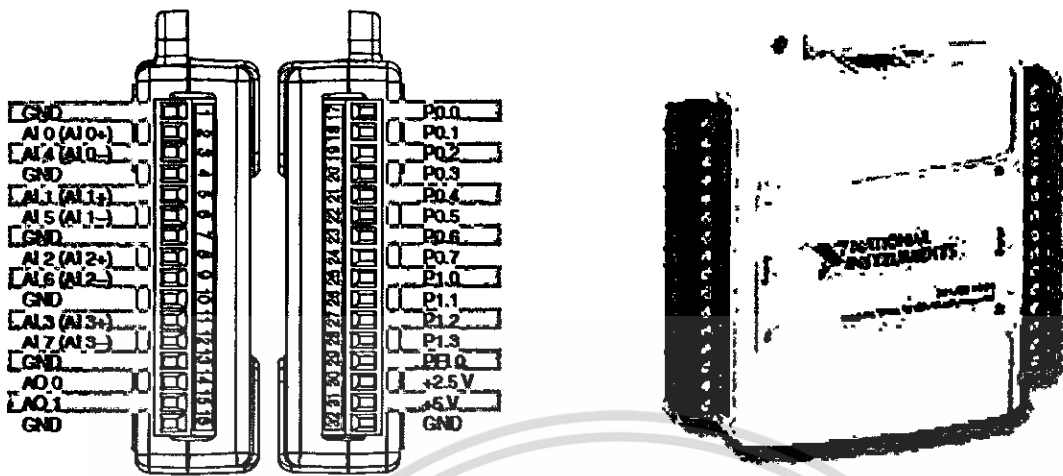
SPECIFICATION

Type	Horizontal water cooled diesel engine										
Injection system	Direct Injection (DI)										
Number of cylinder	6										
Displacement	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
Stroke	130	130	130	130	130	130	130	130	130	130	130
Max. Output	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400	12.5 / 2400
Min. Output	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400	6.5 / 2400
Compression ratio	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1	16.0:1
Fuel injection pump	Common rail										
Injection pressure	200										
Lubrication system	Fully sealed forced lubrication with gear oil pump & hydraulic regulator valve										
Lubricating oil capacity (oil pan)	22										
Cooling system	Water cooled										
Cooling water capacity	1.8	0.4	1.8	2.4	2.1	2.1	11.8	2.1	2.1	11.8	
Dimensions											
Length	876					704					
Width	396					396					
Height	808					808					
Weight	870	870	870	870	870	870	870	870	870	870	870

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A-2: Data acquisition



Signal Name	Reference	Direction	Description
GND	—	—	Ground—The reference point for the single-ended analog input measurements, analog output voltages, digital signals, +5 VDC supply, and +2.5 VDC at the I/O connector, and the bias current return point for differential mode measurements.
AI <0..7>	Varies	Input	Analog Input Channels 0 to 7—For single-ended measurements, each signal is an analog input voltage channel. For differential measurements, AI 0 and AI 4 are the positive and negative inputs of differential analog input channel 0. The following signal pairs also form differential input channels: AI<1, 5>, AI<2, 6>, and AI<3, 7>. Refer to the <i>Analog Input</i> section for more information.
AO <0, 1>	GND	Output	Analog Output Channels 0 and 1—Supplies the voltage output of AO channel 0 or AO channel 1. Refer to the <i>Analog Output</i> section for more information.
P0.<0..7>	GND	Input or Output	Port 0 Digital I/O Channels 0 to 7—You can individually configure each signal as an input or output. Refer to the <i>Digital I/O</i> section for more information.
P1.<0..3>	GND	Input or Output	Port 1 Digital I/O Channels 0 to 3—You can individually configure each signal as an input or output. Refer to the <i>Digital I/O</i> section for more information.
PFI0	GND	Input	PFI 0—This pin is configurable as either a digital trigger or an event counter input. Refer to the <i>PFI 0</i> section for more information.
+2.5 V	GND	Output	+2.5 V External Reference—Provides a reference for wrap-back testing. Refer to the <i>+2.5 V External Reference</i> section for more information.
+5 V	GND	Output	+5 V Power Source—Provides +5 V power up to 200 mA. Refer to the <i>+5 V Power Source</i> section for more information.

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A-4: Pressure sensor

Pressure

Operating Characteristics

Table 1. Operating Characteristics ($V_S = 5.0$ Vdc, $T_A = 25^\circ\text{C}$ unless otherwise noted, $P1 > P2$. Decoupling circuit shown in Figure 4 required to meet electrical specifications.)

Characteristic	Symbol	Min	Typ	Max	Unit
Pressure Range ⁽¹⁾	P_{OP}	0	—	50	kPa
Supply Voltage ⁽²⁾	V_S	4.75	5.0	5.25	Vdc
Supply Current	I_b	—	7.0	10	mAdc
Minimum Pressure Offset ⁽³⁾ @ $V_S = 5.0$ Volts	V_{off}	0.028	0.2	0.313	Vdc
Full Scale Output ⁽⁴⁾ @ $V_S = 5.0$ Volts	V_{FSO}	4.587	4.7	4.813	Vdc
Full Scale Span ⁽⁵⁾ @ $V_S = 5.0$ Volts	V_{FSS}	—	4.5	—	Vdc
Accuracy ⁽⁶⁾	—	—	—	±2.5	% V_{FSS}
Sensitivity	V/P	—	98	—	mV/kPa
Response Time ⁽⁷⁾	t_R	—	1.0	—	ms
Output Source Current at Full Scale Output	I_{out}	—	0.1	—	mAdc
Warm-Up Time ⁽⁸⁾	—	—	29	—	ms
Offset Stability ⁽⁹⁾	—	—	±0.5	—	% V_{FSS}

1. 1.0 MPa (14.503 psi) equals 0.145 psi

2. Device is isometric within this specified excitation range.

3. Offset (V_{off}) is defined as the output voltage at the minimum rated pressure.

4. Full Scale Output (V_{FSO}) is defined as the output voltage at the maximum or full rated pressure.

5. Full Scale Span (V_{FSS}) is defined as the algebraic difference between the output voltage of full rated pressure and the output voltage at the minimum rated pressure.

6. Accuracy (error budget) consists of the following:

Linearity: Output deviation from a straight line relationship with pressure over the specified pressure range.

Temperature Hysteresis: Output deviation of any temperature within the operating temperature range, after the temperature is cycled to and from the minimum or maximum operating temperature points, with zero differential pressure applied.

Pressure Hysteresis: Output deviation at any pressure within the specified range, when this pressure is cycled to and from the minimum or maximum rated pressure at 25°C .

Temperature: Output deviation over the temperature range of 0° to 85°C , relative to 25°C .

Temperature Offset: Output deviation with minimum pressure applied, over the temperature range of 0° to 85°C , relative to 25°C .

Variation from Nominal: The variation from nominal values, for Offset or Full Scale Span, as a percent of V_{FSS} at 25°C .

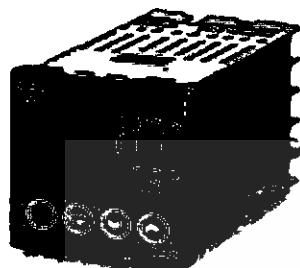
7. Response Time is defined as the time for the incremental change in the output to go from 10% to 90% of its final value when subjected to a specified step change in pressure.

8. Warm-up Time is defined as the time required for the product to meet the specified output voltage after the Pressure has been stabilized.

9. Offset Stability is the product's output deviation when subjected to 1000 hours of Pulsed Pressure, Temperature Cycling with Bias Test.

MPX5050

A-5: Temperature control



- **Indication Accuracy**
 Thermocouple input: $\pm 0.3\%$ of PV (previous models: $\pm 0.5\%$)
 PT input: $\pm 0.2\%$ of PV (previous models: $\pm 0.5\%$)
 Analog input: $\pm 0.2\%$ FS (previous models: $\pm 0.5\%$)
- **New E5CN-U Models (Plug-in Models) with analog inputs and current outputs.**
- **A PV/SV-status display function can be set to automatically alternate between displaying the status of the Temperature Controller (auto/manual, RUN/STOP, and alarms) and the PV or SV.**
- **Preventive maintenance for relays in the Temperature Controller using a Control Output ON/OFF Counter.**

Specifications

Ratings	
Power supply voltage	
No D in model number: 100 to 240 VAC, 50/60 Hz D in model number: 24 VAC, 50/60 Hz, 24 VDC	
Operating voltage range	
85% to 110% of rated supply voltage	
Power consumption	E5CN
	E5CN-U
Sensor input	
Models with temperature inputs Thermocouple: K, J, T, E, L, U, N, R, S, B, W, or PL II Platinum resistance thermometer: PT100 or JPt100 Infrared temperature sensor: 10 to 70°C, 60 to 120°C, 115 to 165°C, or 140 to 260°C Voltage input: 0 to 50 mV	
Models with analog inputs Current input: 4 to 20 mA or 0 to 20 mA Voltage input: 1 to 5 V, 0 to 5 V, or 0 to 10 V	
Input impedance	
Current input: 150 Ω max., Voltage input: 1 M Ω min. (Use a 1:1 connection when connecting the ES2-HB.)	
Control method	
ON/OFF control or 2-PID control (with auto-tuning)	
Control outputs	Relay output
	Voltage output (for driving SSR)
	Current output
	Long-life relay output
Auxiliary outputs	Number of outputs
	Output specifications
Event inputs	Number of inputs
	External contact input specifications
External power supply for ES1B	
Setting method	
Indication method	
Multi SP	
Bank switching	
Other functions	
Ambient operating temperature	
Ambient operating humidity	
Storage temperature	

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A-6: Flow switch

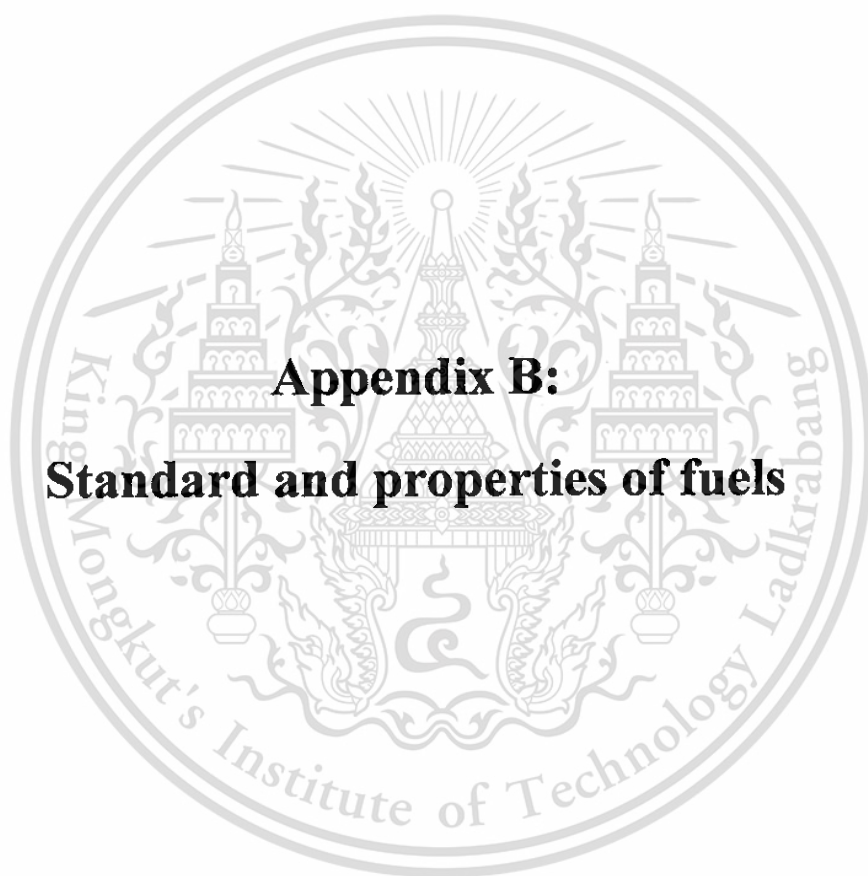
Model	PFM710	PFM725	PFM750	PFM711		
Applicable fluid	Dry air, N ₂ , Ar, CO ₂ (air quality class to ISO8573-1 1.1.2 to 1.6.2)					
Rated flow range	Dry air, N ₂ , Ar	0.2 to 10 L/min	0.5 to 25 L/min	1 to 50 L/min	2 to 100 L/min	
	CO ₂	0.2 to 5 L/min	0.5 to 12.5 L/min	1 to 25 L/min	2 to 50 L/min	
Instantaneous flow	Display flow range	Dry air, N ₂ , Ar	0.2 to 10.5 L/min ^{*1}	0.5 to 26.3 L/min	1 to 52.5 L/min	2 to 105 L/min ^{*2}
		CO ₂	0.2 to 5.2 L/min	0.5 to 13.1 L/min	1 to 26.2 L/min	2 to 52 L/min
	Set flow range	Dry air, N ₂ , Ar	0 to 10.5 L/min ^{*1}	0 to 26.3 L/min	0 to 52.5 L/min	0 to 105 L/min ^{*2}
		CO ₂	0 to 5.2 L/min	0 to 13.1 L/min	0 to 26.2 L/min	0 to 52 L/min
Min. setting/display unit	0.01 L/min		0.1 L/min	0.1 L/min	0.1 L/min	
Accumulated flow	Setting/display flow range ³	0 to 999999 L				
	Min. setting/display unit	1 L				
Accumulated flow volume per pulse	0.1 L/Pulse	0.1 L/Pulse	0.1 L/Pulse	1 L/Pulse		
Display unit	Instantaneous flow: L/min, CFM x 10 ⁻² Accumulated flow: L, ft ³ x 10 ⁻¹					
Reference condition ⁴	Standard condition (ANR), Normal condition (NOR)					
Repeatability	±1%F.S. max. (fluid: Dry air) Analogue output accuracy: ±3%F.S. max.					
Pressure characteristics	±5%F.S. max. (0.35 MPa reference)					
Temperature characteristics	±2%F.S. max. (15 to 35 °C) ±5%F.S. max. (0 to 15 °C, 35 to 50 °C)					
Rated pressure range	-70 to 750 kPa					
Proof pressure	1 MPa					
Switch output	NPN or PNP open collector output					
Switch output	Max. load current	80 mA				
	Max. load voltage	28 VDC (NPN output)				
	Internal voltage drop	NPN output: 1 V (at 80 mA), PNP output: 1.5 V or less (at 80 mA)				
	Response time	1 s (50 ms, 0.5 s, 2 s are selectable)				
	Output protection	Short circuit protection				
	Output mode	Hysteresis mode, window comparator mode, Accumulated output mode, Accumulated pulse output mode				
	Hysteresis	Variable				
Analogue output	Response time	1.5 s				
	Voltage output	Output voltage: 1 to 5 V Output impedance: 1 kΩ				
	Current output	Output current: 4 to 20 mA Max. load impedance: 600 Ω (24 VDC) Min. load impedance: 50 Ω				
	Accuracy	±5%F.S. max.				

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Model	PFM710	PFM725	PFM750	PFM711
External input	Voltage free input (reed switch or solid state), 30 ms or more			
Display accuracy	±3%F.S. max. (fluid: Dry air)			
Display	3 digits, 7 segment, dual colour display (red/green)			
Indicator LED	LED is ON when output is ON OUT1: Green OUT2: Red			
Supply voltage	24 VDC± 10%			
Power consumption	55 mA			
Environment	Enclosure	IP40		
	Operating fluid temperature	0 to 50 °C (no freezing or condensation)		
	Operating temp. range	Operating: 0 to 50 °C, Stored: -10 to 60 °C (no freezing or condensation)		
	Operating humidity range	Operating, stored 35 to 85% R.H. (no condensation)		
	Withstand voltage	1000 VAC, 1 min. between terminals and case		
	Insulation resistance	50 MΩ min. (at 500 VDC) between terminals and case		

- 1: If the resolution is set to 1000 for 10 L/min type, the display upper limit will be [9.99 L/min].
- 2: If the resolution is set to 1000 for 100 L/min type, the display upper limit will be [99.9 L/min].
- 3: When using the Accumulated flow hold function, calculate the product life according to the operating conditions, and use the product within its life. The limit of the number times the memory can be written to is 1 million times. If the product is operated 24 hours per day, the life will be as follows.
 - Data stored every 5 minutes: 5 minutes x 1 million cycles = 5 million minutes = 8.5 years
 - Data stored every 2 minutes: 2 minutes x 1 million cycles = 2 million minutes = 3.8 years
 If the accumulated flow external reset is repeatedly input, the life will be shorter than the calculated life.
- 4: Standard condition (ANSI): Flow measurement reference condition 101.3 kPa, 20 °C, 65%R.H.
Normal condition (NOR): Flow measurement reference condition 101.3 kPa, 0 °C.



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B-1: Diesel fuel

รายละเอียดคุณสมบัติของน้ำมันดีเซลที่จำหน่าย
 เรื่อง กำหนดลักษณะและคุณภาพของน้ำมันดีเซล (ฉบับที่ ๕)
 พ.ศ. ๒๕๕๔

รายการ	ข้อกำหนด	อัตราสูงสุดต่ำ	น้ำมันดีเซล		วิธีทดสอบ ^๑
			หมุนเร็ว	หมุนช้า	
1	ความถ่วงจำเพาะ ณ อุณหภูมิ 15.6/15.6 องศาเซลเซียส (Specific Gravity at 15.6/15.6 °C)	ไม่ต่ำกว่า และ ไม่สูงกว่า	0.81 0.87	- 0.920	ASTM D 1298
2	จำนวนซีเทน (Cetane Number) หรือ ดัชนีซีเทน (Calculated Cetane Index)				ASTM D 613 ASTM D 976
	ก่อนวันที่ 1 มกราคม พ.ศ. 2555	ไม่ต่ำกว่า	47	45	
	ตั้งแต่วันที่ 1 มกราคม พ.ศ. 2555 เป็นต้นไป	ไม่ต่ำกว่า	50	45	
3	ความหนืด (Viscosity, °C)				ASTM D 445
	3.1 ณ อุณหภูมิ 40 องศาเซลเซียส (at 40 °C)	ไม่ต่ำกว่า และ ไม่สูงกว่า	1.8 4.1	- 8.0	
	หรือ 3.2 ณ อุณหภูมิ 50 องศาเซลเซียส (at 50 °C)	ไม่สูงกว่า	-	6.0	
4	จุดไหลแหว (Pour Point, °C)	ไม่สูงกว่า	10	16	ASTM D 97
5	กำมะถัน (Sulphur, %wt.)				
	ก่อนวันที่ 1 มกราคม พ.ศ. 2555	ไม่สูงกว่า	0.035	1.5	ASTM D 4294
	ตั้งแต่วันที่ 1 มกราคม พ.ศ. 2555 เป็นต้นไป	ไม่สูงกว่า	0.005	1.5	ASTM D 2622
6	การกัดกร่อนแผ่นทองแดง (Copper Strip Corrosion)	ไม่สูงกว่า	หมายเลข 1	-	ASTM D 130
7	เสถียรภาพต่อการเกิดปฏิกิริยา ออกซิเดชัน (Oxidation Stability, g/m ³)	ไม่สูงกว่า	25	-	ASTM D 2274
8	คาร์บอน (Carbon Residue, %wt.)	ไม่สูงกว่า	0.05	-	ASTM D 189
9	น้ำและตะกอน (Water and Sediment, %vol.)	ไม่สูงกว่า	0.05	0.3	ASTM D 2709
10	เถ้า (Ash, %wt.)	ไม่สูงกว่า	0.01	0.02	ASTM D 482

(๕๒ -)

รายการ	ข้อกำหนด	ขีดจำกัดค่า	น้ำมันดีเซล		วิธีทดสอบ ¹²	
			หมุนเร็ว	หมุนช้า		
11	จุดวาบไฟ (Flash Point,	องศาเซลเซียส °C	ไม่ต่ำกว่า	52	52	ASTM D 93
12	การกลั่น (Distillation, สูญเสียของเหลวส่วนที่กลั่นได้โดยปริมาณในอัตราหรือคะแนนที่สิบ (90% recovered)	องศาเซลเซียส °C	ไม่สูงกว่า	357	-	ASTM D 86
13	ไฮโดรคาร์บอนอะโรมาติกโพลไซคลิก (Polycyclic Aromatic Hydrocarbon, ก่อนวันที่ 1 มกราคม พ.ศ. 2555 สิ้นวันที่ 1 มกราคม พ.ศ. 2555 เป็นต้นไป	ร้อยละโดยน้ำหนัก % wt.)	- ไม่สูงกว่า	- 11	- -	ASTM D 2425
14	สี (Colour)					
	14.1 ขนึ้ของสี (Hue)			เหลือง	น้ำตาล	
	14.2 ความเข้มของสี (Intensity)		ไม่ต่ำกว่า และ ไม่สูงกว่า	- 4.0	4.5 7.5	ASTM D 1500
15	ไมโอดีเอสเทอร์ประเภทกรดไขมัน (Methyl Ester of Fatty Acid, ของกรดไขมัน	ร้อยละโดยปริมาตร %vol.)	ไม่ต่ำกว่า และ ไม่สูงกว่า	3 5	- -	EN 14078
16	คุณสมบัติการหล่อลื่น รอยขีดข่วน (Lubricity, Wear Scar	ไมโครเมตร μm)	ไม่สูงกว่า	460	-	CEC F-06-96
17	สารเติมแต่ง (ถ้ามี) (Additive)		ไม่มีเปลี่ยนแปลงที่ได้รับความเห็นชอบจากอธิบดี กรมธุรกิจพลังงาน			

หมายเหตุ 12 วิธีทดสอบอาจใช้วิธีอื่นที่เทียบเท่าก็ได้ แต่ไม่ควรมีค่าที่น้อยกว่าวิธีที่ใช้วิธีที่กำหนดไว้ภายใต้เงื่อนไขการทดสอบที่เหมือนกัน

B-2: Biodiesel fuel

รายละเอียดแบบท้ายประกาศกรมธุรกิจพลังงาน
เรื่อง กำหนดลักษณะและคุณภาพของไบโอดีเซลประเภทเมทิลเอสเตอร์ของกรดไขมัน

พ.ศ. ๒๕๕๒

รายการ	ชื่อพิกัด	หน่วย	ขีดจำกัด	ค่า	วิธีทดสอบ ²
1	เมทิลเอสเตอร์ (Methyl Ester)	ร้อยละโดยน้ำหนัก (% wt.)	ไม่ต่ำกว่า	96.5	EN 14103
2	ความหนาแน่น ณ อุณหภูมิ 15 °C (Density at 15 °C)	กิโลกรัม/ลูกบาศก์เมตร (kg/m ³)	ไม่ต่ำกว่า และ ไม่สูงกว่า	860 900	ASTM D 1298
3	ความหนืด ณ อุณหภูมิ 40 °C (Viscosity at 40 °C)	เซนติโสต (cSt)	ไม่ต่ำกว่า และ ไม่สูงกว่า	3.5 5.0	ASTM D 445
4	จุดวาบไฟ (Flash Point)	องศาเซลเซียส (°C)	ไม่ต่ำกว่า	120	ASTM D 93
5	กำมะถัน (Sulphur)	ร้อยละโดยน้ำหนัก (%wt.)	ไม่สูงกว่า	0.0010	ASTM D 2622
6	คาร์บอน (ร้อยละ 10 ของกากที่เหลือจากการกลั่น) (Carbon Residue, on 10 % distillation residue, %wt)	ร้อยละโดยน้ำหนัก (%wt)	ไม่สูงกว่า	0.30	ASTM D 4530
7	จำนวนซีเทน (Cetane Number)		ไม่ต่ำกว่า	51	ASTM D 613
8	เถ้าฟอสเฟต (Sulphated Ash)	ร้อยละโดยน้ำหนัก (%wt.)	ไม่สูงกว่า	0.02	ASTM D 874
9	น้ำ (Water)	ร้อยละโดยน้ำหนัก (wt.)	ไม่สูงกว่า	0.050	EN ISO 12937
10	สิ่งปนเปื้อนทั้งหมด (Total Contaminants)	ร้อยละโดยน้ำหนัก (%wt.)	ไม่สูงกว่า	0.0024	EN 12662
11	การกัดกร่อนแถบทองแดง (Copper Strip Corrosion)		ไม่สูงกว่า	หมายเลข 1	ASTM D 130
12	เสถียรภาพต่อการเกิดปฏิกิริยา ออกซิเดชัน ณ อุณหภูมิ 110 องศาเซลเซียส (Oxidation Stability at 110 °C)	ชั่วโมง (hours)	ไม่ต่ำกว่า	10	EN 14112

(ต่อ-2)

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รายการ	ชื่อกำหนด	ขีดจำกัด	วิธีทดสอบ ^{1/}
13	ค่าความเป็นกรด (Acid Value . มีผลต่อปริมาณโพแทสเซียมไฮดรอกไซด์ต่อกรัม mg KOH/g)	ไม่สูงกว่า	0.50 ASTM D 664
14	ค่าไอโอดีน (Iodine Value . กรัมไอโอดีน / 100 กรัม g iodine / 100 g)	ไม่สูงกว่า	120 EN 14111
15	กรดลิโนเลนิกเมทิลเอสเตอร์ (Linolenic Acid Methyl Ester . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	12.0 EN 14103
16	เมทานอล (Methanol . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.20 EN 14110
17	โมโนกลีเซอไรด์ (Monoglyceride ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.60 EN 14105
18	ไดกลีเซอไรด์ (Diglyceride . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.20 EN 14105
19	ไตรกลีเซอไรด์ (Triglyceride . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.20 EN 14105
20	กลีเซอรินอิสระ (Free glycerin . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.02 EN 14105
21	กลีเซอรินทั้งหมด (Total glycerin . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.25 EN 14105
22	โลหะกลุ่ม 1 (โซเดียมแคลโปแตสเซียม) (Group I metals (Na+K). มีผลต่อปริมาณโพแทสเซียม mg/kg)	ไม่สูงกว่า	5.0 EN 14108 และ EN 14109
	โลหะกลุ่ม 2 (แคลเซียมแมกนีเซียม) (Group II metals (Ca+Mg). มีผลต่อปริมาณโพแทสเซียม mg/kg)	ไม่สูงกว่า	5.0 pr EN 14538
23	ฟอสฟอรัส (Phosphorus . ร้อยละโดยน้ำหนัก %wt.)	ไม่สูงกว่า	0.0010 ASTM D 4951
24	สารเติมแต่ง (ตัวสี) (Additive)	ให้เป็นไปตามที่ได้รับความเห็นชอบจากอธิบดี กรมธุรกิจพลังงาน	

หมายเหตุ 1/ วิธีทดสอบอาจใช้วิธีอื่นที่เทียบเท่ากันได้ แต่ในกรณีที่มีข้อโต้แย้งให้ใช้วิธีที่กำหนดในตารางนี้เป็นแบบเท่านั้น



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C-1: Thailand emission standards for small diesel engine vehicle

ประกาศกระทรวงอุตสาหกรรม

ฉบับที่ ๔๓๕๔ (พ.ศ. ๒๕๕๔)

ออกตามความในพระราชบัญญัติมาตรฐานผลิตภัณฑ์อุตสาหกรรม

พ.ศ. ๒๕๑๑

เรื่อง กำหนดมาตรฐานผลิตภัณฑ์อุตสาหกรรม

รถยนต์ขนาดเล็กที่ใช้เครื่องยนต์แบบจุดระเบิดด้วยการอัด เฉพาะด้านความปลอดภัย :

สารมลพิษจากเครื่องยนต์ ระดับที่ 7

หน่วยเป็น g/km

ประเภทรถยนต์	น้ำหนักจริง (kg)	คาร์บอน มอนอกไซด์	ออกไซด์ ของ ไนโตรเจน	ไฮโดรคาร์บอนรวม กับออกไซด์ ของ ไนโตรเจน	สารมลพิษ อนุภาค
รถยนต์นั่ง หมวดเครื่องยนต์บรรทุกไม่เกิน 2 500 kg	-	0.50	0.25	0.30	0.025
รถยนต์นั่งหมวดเครื่องยนต์บรรทุกเกิน 2 500 kg หรือรถยนต์บรรทุกเฉพาะรถยนต์นั่งที่ดัดแปลงมา จากรถยนต์บรรทุกที่มีน้ำหนักเครื่องยนต์บรรทุกไม่เกิน 3 500 kg	ไม่เกิน 1 305	0.50	0.25	0.30	0.025
	เกิน 1 305 แต่ไม่เกิน 1 760	0.63	0.33	0.39	0.04
	เกิน 1 760	0.74	0.39	0.46	0.06



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The 21st

Small Engine Technology Conference

Small Engines, The Key to a Prosperous Society

Osaka International Convention Center
(Grand Cube Osaka)
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Characterization of Biodiesel Particle Emission in Trapping and Regeneration Processes on Cordierite Diesel Particulate Filter

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ABSTRACT

As well-known, the diesel engine has the highest thermal efficiency at the same load as compared with internal combustion engine but its disadvantage is particulate matter (PM) emitted to the atmosphere. The studies of this paper were divided into two parts. The first part studied the quantity of PM from the both diesel and biodiesel fuels at 80% load (2400 rpm) by the trapping process on diesel particulate filter (DPF) used in a partial flow dilution tunnel. The second part studied the regeneration process of PM under the flow rate of oxygen and nitrogen gas of 13.5 L/min with 10%, 15%, and 21% of oxygen gas. The result showed that amount of PM from biodiesel fuel was lower around two times than PM from diesel fuel. The duration in regeneration process of biodiesel's PM was shorter than diesel while increasing of oxygen percentage can reduce regeneration time.

Keywords: Diesel Engine, Diesel particulate filter, Particulate Matter, Biodiesel

INTRODUCTION

The considerable amount of energy is used in transportation sector and vital demand is met through diesel engine from all over the world due to its high thermal efficiency when compared with other internal combustion engines. However, the main pollutants from diesel engine are solid particles (Particulate Matter: PM) and nitrogen oxide (NO_x). The pollutants should be removed from exhaust gas because of their effects on environment and human health, such as lung cancer. Thus, the regulation of vehicle emissions has become increasingly stringent. Diesel particulate filter (DPF) is one way to reduce the PM from diesel engine by way of PM trapping and oxidation.

Generally, DPF is made from ceramic material such as cordierite or silicon carbide, consisting of many rectangular channels with alternate channel blocks using cement at each end. In trapping process, the exhaust gas will flow through a channel wall having various micron-scale pores that trap the particle emissions. In addition, the PM must be oxidized to regenerate the DPF and reduce the back pressure on the diesel engine. [1-3]

Diesel particulate matters consist of a solid fraction (SOL) and a soluble organic fraction (SOF). Primary particles, composed of carbon and metallic ash, are coated with SOF and sulfate. The microstructures of primary soot particles have been characterized using transmission electron microscopy (TEM) to understand them in detail. The mean diameter of the primary and agglomerated particles is usually in the range of 20-80 nm and 80-300 nm, respectively. The composition of particles from a diesel engine may vary widely depending on the operating conditions and fuel composition [4-10]. The engine condition has many effects to particulate matter. First, there was a large variation in overall particulate sizes. Second, particulates had different shapes with grape-like structures. Third, more particles were deposited onto a grid as the engine load was increased [11-13]. As for DPF mechanism, the oxidation reaction of soot has been investigated using thermogravimetric analysis (TGA) and temperature program oxidation (TPO) to evaluate catalytic activities [14-17].

With depleting fossil diesel resources, another alternative fuel, such as biodiesel, is good choice for usage instead of diesel fuels. The main advantages of biodiesel over diesel fuel are its very low sulfur and aromatic hydrocarbon content. In addition, biodiesel includes oxygen molecule, which also acts like environmental friendly fuel. Oxygenated content in biodiesel molecule helps achieve more complete combustion, resulting less and smaller size of particulate matter than that of diesel fuel. Moreover,

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biofuel fuel can substantially reduce net global warming gas (CO₂) due to its carbon-neutral nature. In other words, carbon emitted from combustion of biofuel into atmosphere is compensated by life-time carbon intake during plant photosynthesis.

METHODOLOGY

Engine

The small diesel engine is used to generate particulate matter for condition of diesel and biofuel combustion. The engine specification is four-stroke single cylinder of 638 cc displacement, direct injection with a rated output of 8.8 kW. The fuel injection pressure was approximately 19.6 MPa. The engine was operated by constant speed at 2400 rpm under 80% load on the Eddy current engine dynamometer (Tokyo plant ED-60-LC).

Fuel

A conventional diesel fuel (B4-5) was used and compared with the results of biofuel fuel derived from palm-olein (B100: TIS 2313-2549). Distillation curves (Temperature-Vaporization) of both fuels are shown in Figure 1[18]. It was clearly observed that diesel fuel could be distilled in wide range of temperature due to fossil fuel consisting of many kind of molecules; whereas, biofuel with less variety of molecules could vaporize at the narrower temperature. The distillation temperature of biofuel is higher than that of diesel at the same fraction. Therefore, the high temperature inside the biofuel engine combustion chamber will be reduced [18].

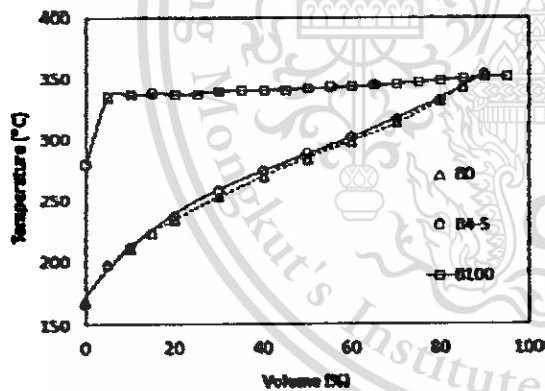


Figure 1. Distillation curves of palm-olein biofuel (B100) and conventional diesel (B4-5) in Thailand.

Experimental setup for Trapping and Regeneration

Figure 2 shows a schematic diagram of experimental setup for PM trapping. The exhaust gas was flown into the small DPF through a bypass line, which a DPF was installed in the pipe. The process was operated at constant temperature of approximately 200 °C. The quantity of PM was measured by pressure sensor, which was installed behind and in front of DPF. The pressure in the process was scrubbed from the combustion and vacuum pump.

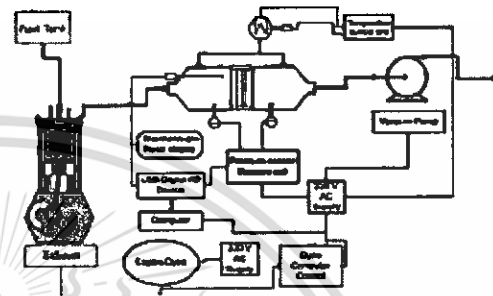


Figure 2. Experimental setup for trapping PM

Figure 3 shows a schematic diagram of experimental setup for DPF regeneration. After the engine stopped and DPF was full, nitrogen and oxygen gases were released through the swirl DPF for oxidation with PM at constant temperature of approximately 600 °C. The gas flow rate in regeneration process was at 13.5 L/min with 10%, 15% and 21% of oxygen gas, which was controlled by flow switch.

The signals from all of devices in both process was transferred to isolated USB digital I/O module to convert signals to data was transferred to show and record in a computer.

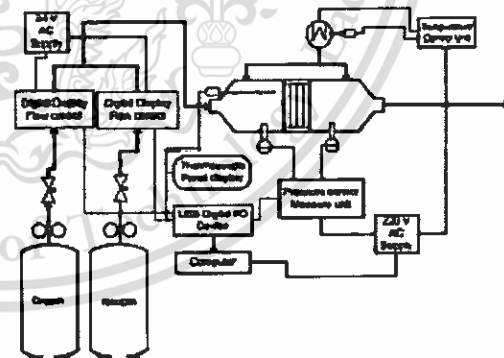
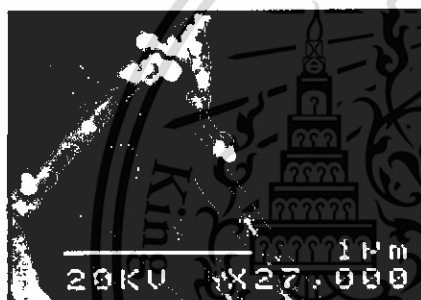


Figure 3. Experimental setup for regeneration PM

RESULTS

PM size distribution

The PM structures have been characterized by using scanning electron microscope (SEM) and transmission electron microscope (TEM) to understand their details. The particulate size distribution in agglomerated mode consisting of approximately 100 particles, which was taken from SEM image, was shown in Figure 4. Most of diesel particle size was around 120 - 140 nm while the biodiesel particle size has peaked in the smaller size range between 90 - 110 nm. The particulate size distribution in primary mode consisting of approximately 100 particles, which was taken from TEM image, was shown in Figure 5. Most of diesel particle size was around 50-60 nm while the biodiesel particle size has peaked in the smaller size range between 30-40 nm. This is due to the lower concentration of biodiesel particle, which is readily oxidized with more available oxygen in combustion flame from oxygenated biodiesel fuel. Moreover, higher oxygen content and homogeneity mixture close to the stoichiometric condition of bio-oxygenated fuel can produce smaller size of primary particulate particle [18-20].

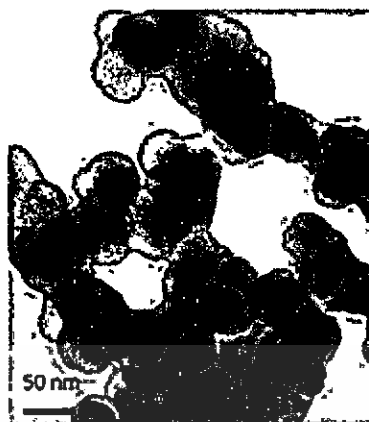


(a) Diesel agglomerate PM



(b) Biodiesel agglomerate PM

Figure 4. SEM images of (a) Diesel PM and (b) Biodiesel PM



(a) Diesel primary PM



(b) Biodiesel primary PM

Figure 5. TEM images of (a) Diesel PM and (b) Biodiesel PM

PM quantity

Figure 6 shows the result of average PM's flow rate, which was trapped by air filter at 10, 20, 30 and 40 seconds, for both biodiesel and diesel fuels. The biodiesel PM's flow rate was around 0.06-0.07 g/min while diesel PM's flow rate was approximately twice, around 0.12-0.13 g/min.

Figure 7 shows the result of PM trapping behavior. Pressure drop between inlet and outlet of the filter during diesel PM trapping took duration around 3000 seconds; whereas, biodiesel PM trapping took around 1500 second. In other words, trapping process of biodiesel PM had duration approximately double that of diesel.

From the results of both cases, more soot particle was remained in diesel combustion than those of biodiesel because biodiesel fuel consisting of more oxygen atom in fuel molecule is readily oxidized with available oxygen in the flame zone. Therefore, PM concentration from bio-oxygenated fuel combustion is lower than diesel's combustion.

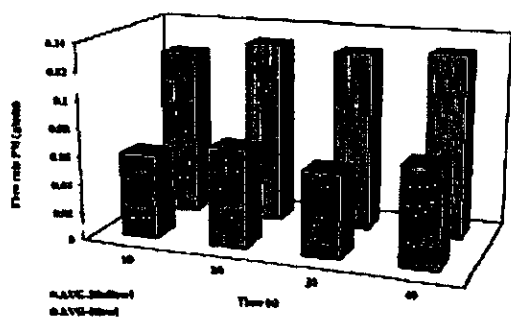


Figure 6. Average PM's flow rate of diesel and biodiesel.

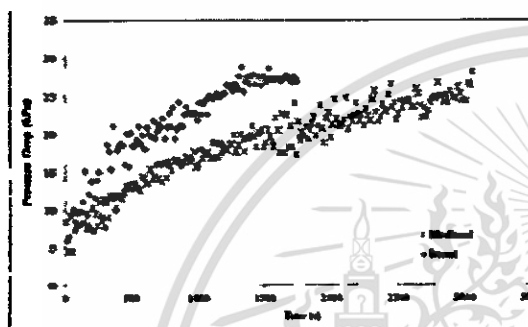
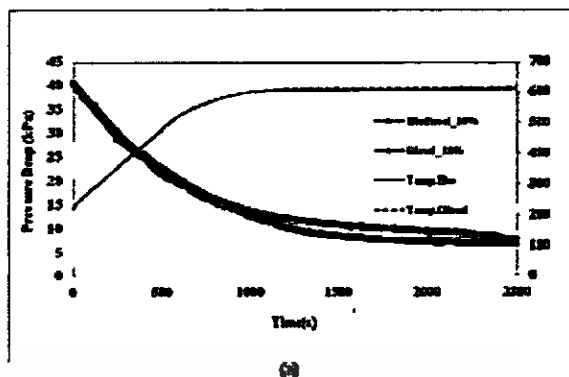
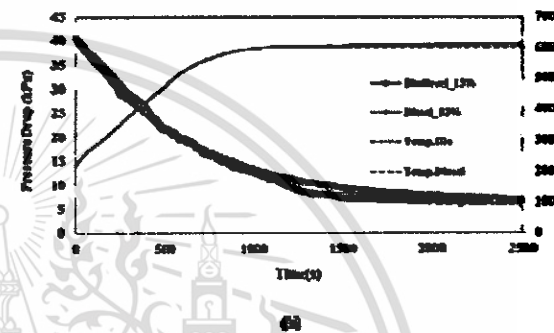


Figure 7. Pressure differential of diesel and biodiesel in trapping process.



PM Oxidation

Figure 8 (a), (b) and (c) show the results of DEP regeneration behaviors between diesel and biodiesel at 16%, 15% and 21% oxygen. Pressure drop of diesel and biodiesel at the beginning state was decreased in the similar manner. However, at temperature around 600 °C, the pressure drop of biodiesel became lower than diesel. In all of regeneration conditions, similar result of faster pressure drop was observed for biodiesel.

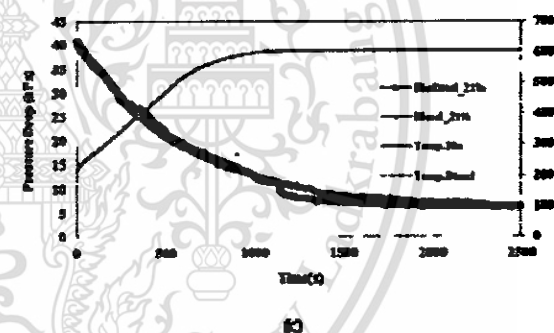


Figure 9 shows the result of pressure drop in regeneration process comparing between 16%, 15% and 21% of oxygen with (a) biodiesel and (b) diesel. The result of diesel and biodiesel was similar. At the beginning, pressure drop of all conditions was decreased in the similar fashion until a pressure drop of 18-15 kPa, where the higher oxygen content, the slightly faster the pressure drop.

Figure 8. Pressure differential of regeneration process by using oxygen (a) 16%, (b) 15% and (c) 21%.

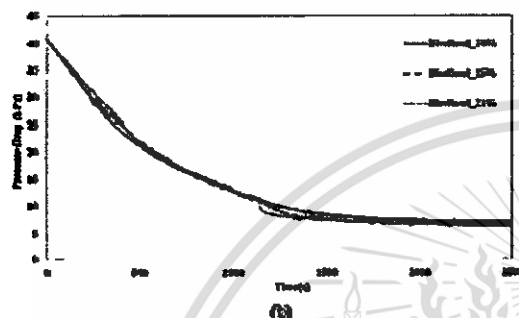
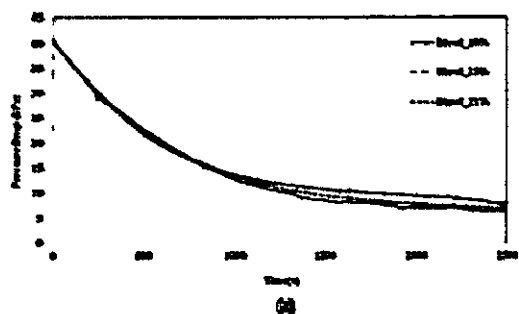


Figure 9. Pressure drop of DPF regeneration process at 10%, 15%, and 21% (a) diesel and (b) biodiesel.

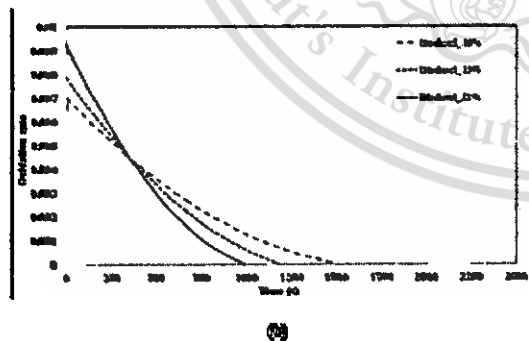
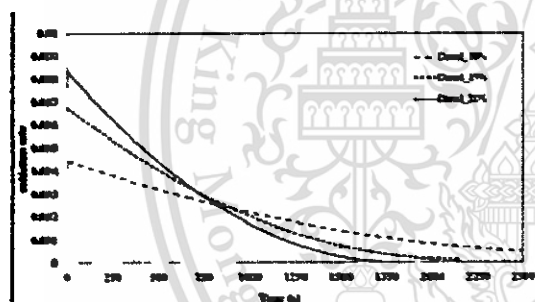


Figure 10. Oxidation rate of particulate matter with (a) diesel and (b) biodiesel.

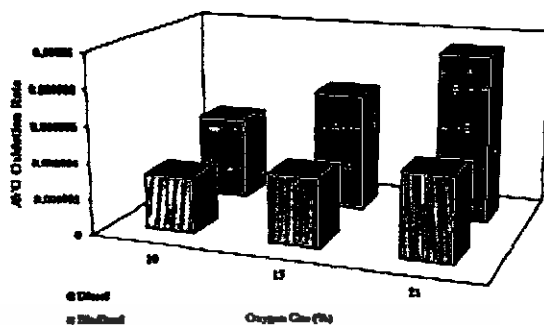


Figure 11. Oxidation rate of PM at 10%, 15% and 21% oxygen.

Figure 10 shows the result of oxidation rate of PM at various oxygen percentages of 10%, 15% and 21% with (a) biodiesel and (b) diesel. The oxidation rate of 21% was the highest as compared with 10% and 15% so the times of PM oxidation were shortest. In other words, the concentration of oxygen in system affected the oxidation of PM.

Figure 11 shows the result of average oxidation rate of PM between diesel and biodiesel at 10%, 15% and 21% of oxygen. From the results, the oxidation rate of biodiesel was higher than diesel for all conditions and percentages of oxygen with higher oxidation rate from more oxygen percentage.

From all of results, it can be explain that, during initial regeneration stage, the pressure was decreased from oxidation of moisture and unburned hydrocarbon, followed by carbon oxidation at the temperature around 600°C. The oxidation rate increased with amount of oxygen because oxygen could react with PM. Furthermore, biodiesel PM oxidized better than diesel because the size of biodiesel PM was smaller than that of diesel.

SUMMARY/CONCLUSIONS

The PM size of diesel particles is larger than that of biodiesel because of lower concentration of biodiesel particles, which is mostly oxidized with some available oxygen in combustion flame due to oxygenated biodiesel fuel. However, the PM size did not significantly affect DPF trapping process because the pore size of DPF is very large compared to the size of the particle emission.

Biodiesel fuel combustion produces particulate matters about half of that from diesel combustion. Therefore, the conventional DPF can be used for double trapping duration. This implies that the energy consumption of engine for both the effect of pressure drop while driving and DPF regeneration process could be reduced by half.

The amount of oxygen can affect PM's oxidation rate because oxygen gas will react with much carbon to decrease the regeneration duration.

The PM of biodiesel can be oxidized faster than PM of diesel because biodiesel emits a smaller PM size and less oxygen atoms in hydrocarbon phase, which helps promote PM oxidation.

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