

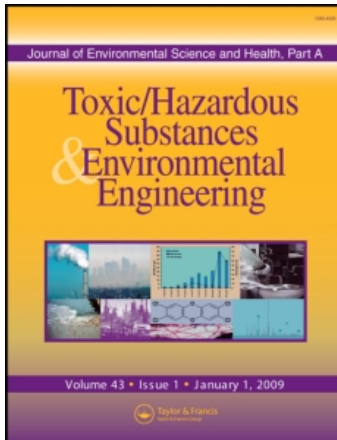
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THE EMISSION CHARACTERISTICS OF A SMALL D.I. DIESEL ENGINE USING BIODIESEL BLENDED FUELS

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ABSTRACT

Biodiesel and biodiesel blends provide low emissions without modification on the fuel system of conventional diesel engines. This study aims to develop a new domestic biodiesel production procedure which makes use of waste fryer vegetable oil by transesterification method, and further investigates the emission characteristics of a small D.I. diesel engine using biodiesel blends and diesel fuels, respectively. The 20/80 and 30/70 blends of biodiesel to diesel fuel are used in this study. The emission characteristics include smoke emissions, gaseous emissions (CO, HC, NO_x and SO₂), particle size distributions and number concentrations at a variety of steady state engine speed points. We have found that diesel engine fueled with biodiesel blends emits more PM₂ particle number concentrations than those with diesel fuel, and PM₂ number concentration increases as biodiesel concentration increases. As for the smoke and gaseous emissions, such as CO, HC, NO_x and SO₂, the results favored biodiesel blends.

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Key Words: Particulate; Diesel engine; Biodiesel blends; Alternative fuel; PM_{2.5}.

INTRODUCTION

Diesel engines have been identified as a significant mobile source of both oxides of nitrogen (NO_x) and particulate matter (PM). NO_x is a precursor to ozone formation in the lower atmosphere and diesel particulate emissions contribute to overall ambient air particulate mass. The continuing growth of the diesel engines being used has raised a great concern about the effects, which the NO_x and PM emissions may have caused on the environment and general public health. The entire engine industry has been devoted to the research and development of low emission technologies, such as modified combustion processes, improved fuel injection system, exhaust after-treatment system, or development of alternative fuels technology.

Due to increasing environmental awareness, biodiesel is gaining recognition in the advanced nations, such as U.S.A., France and Austria, as a renewable fuel and it may be used as an alternative to diesel fuel with no engine modifications. Biodiesel can be made from alcohol and vegetable oils, which are both agriculturally derived products. Biodiesel made from such renewable resources is safer due to increased flash point, biodegradable, containing little or no sulfur, tending to reduce visible smoke from the exhaust, and an environmentally innocuous nature. Currently, biodiesel is very expensive to make from new feedstocks. One way to reduce the cost of biodiesel is to use less expensive feedstocks such as waste fryer oil from the food processing industry [1–3]. Methyl esters from vegetable oils (biodiesel) have many characteristics that make them attractive as a fuel for combustion in direct injection compression ignition engines [4–6]. Compared with diesel fuel, combustion of methyl esters was known to reduce smoke opacity, particulate matter (PM), hydrocarbons and carbon monoxide emissions while slightly increasing NO_x emissions and delivering comparable engine performance [2, 3, 7–9]. Likewise biodiesel/diesel blends have also shown similar performance and emissions to diesel fuel while burned in unmodified diesel engines [4–6]. The 20/80 and 30/70 blends of biodiesel to diesel fuel are used in this study because they were determined to be the optimum ratio for a biodiesel/diesel blends by many studies [3, 9, 10].

According to the aforementioned studies, it has been shown that biodiesel and biodiesel blends provides low emissions with much lower smoke opacity, particulate matter (PM), hydrocarbons and carbon monoxide emissions while slightly increasing NO_x emissions and delivering comparable engine performance without modification on the fuel system of conventional diesel engines. Thus biodiesel and biodiesel blends provided an excellent opportunity of emissions reduction for compression ignition engines. This

study is then pursued to further investigate a new domestic biodiesel production procedure, and the emission characteristics of a small D.I. diesel engine using blends of diesel fuel and methyl ester from waste fryer oil. The emission characteristics include smoke emissions, gaseous emissions (NO_x , CO, HC and SO_2).

Particulate emissions from internal combustion engines have traditionally been regulated solely on basis of total particulate mass emissions (g/mile for light duty diesel vehicles or g/bhp-hr for heavy-duty diesel engines); no reference is made either to the size or the number concentration of the emitted particles. In response to these regulations, modern engines have been developed to be capable of emitting much lower particle mass concentrations. Unfortunately, the reduction in particle mass emissions may be accompanied by a dramatic increase in the particle number emissions of fine particles ($<2.5\ \mu\text{m}$) [11–14]. A recent report released by the Health Effects Institute shows that a modern high-pressure direct injection diesel engine emits at least one-order of magnitude higher number concentrations than older technology engines [12]. An example of this is the reduction of the total mass emissions of motor vehicles in the U.S. by a factor of about 10, accompanied at the same time by an increase in the of number of fine particles ($<2.5\ \mu\text{m}$) emitted by a factor of about 20 [14].

Recent epidemiological studies have indicated that the most dangerous particles have diameter $<2.5\ \mu\text{m}$ and a more stringent standard has been promulgated by the U.S. EPA ($\text{PM}_{2.5}$). These health effects are of special pertinence to diesel engine emissions. Particulate emissions in diesel exhausts that range in size from small 10–30 nm spheres to clusters (agglomerates) of these spherules with diameters up to $10\ \mu\text{m}$, are a major source of the most hazardous aerosols [15]. ISO/CEN has developed a respirable dust convention (ISO 7708, 1994) which defines fractions of airborne particles in term of their likely potential to deposit in various regions within the respiratory tract: Throacic fraction – mass fraction of inhaled particles that penetrate the respiratory system beyond the larynx – MAD (median aerodynamic diameter) $10\ \mu\text{m}$.

Respirable fraction – mass fraction of inhaled particles which penetrate the respiratory system to the alveolar region – MAD $4\ \mu\text{m}$. ‘High risk’ respirable fraction – MAD $2.5\ \mu\text{m}$. The size of airborne particles determines in which parts of the respiratory tract the particles are deposited. Small airborne particles less than $2.5\ \mu\text{m}$ in diameter (fine particles) have a high probability of deposition deeper in the respiratory tract are likely to trigger or exacerbate respiratory diseases. Small particles have also higher burdens of toxins, which when absorbed in the body can result in health consequences other than respiratory health effects [14].

Although a considerable amount of effort has been devoted to the measurement and characterization of particulate emissions from diesel engines over the past twenty years. It is only recently that there has been

much information published about the efforts of vehicle and fuel type on particle size [11, 13, 16–18]. All of these studies suggest those particulate emissions from spark ignition engines and using alternative fuels (such as CNG, dimethoxy methane additive on diesel) have the potential to significantly impact public health and the environment. As has previously been stated, diesel engine fueled with biodiesel blends has shown itself to be especially advantageous from both performance and emissions points of view. According to the aforementioned studies, the engines with lower emission rate while with high particulate number concentration may have the potential to significantly impact public health and the environment. This study is then pursued to make an attempt on measuring particle size distributions and number density from a diesel engine fueled with biodiesel/diesel blends at a variety of steady state speed points.

MATERIALS AND METHODS

Engine and Apparatus

A commercial small direct injection diesel engine (LA70AE–SETM) was directly put in use in the present study without further modifications. It was a single cylinder diesel engine with industrial application, manufactured by Yanmar Diesel Engine CO., LTD. The specifications for this engine were as showed in Table 1. The engine operated with 20% blend, 30% blend and pure diesel fuels respectively, and then were investigated the exhaust emission characteristics at a variety of steady state engine speeds, namely 1400, 2000, 2600, 3200 and 3600 rpm. The exhaust emission characteristics include smoke emissions, gaseous emissions (NO_x , CO, HC and SO_2), particle size distributions and number concentrations.

Fuel Production

Biodiesel, as defined by the United States National Biodiesel Board (NBB), is composed of “esters derived from oils and fats from renewable biological sources”. This refers to primarily modified vegetable oils made from a process called transesterification. Transesterification involves mixing an alcohol with a catalyst and combining that mixture with vegetable oil,

Table 1. Engine Specifications

No. of Cylinder	1
Displacement	296cc
Compression Ratio	21:1
Rated Output	6 hp/3600 rpm
Maximum Output	6.7 hp/3600 rpm

allowing the glycerin to settle. The generated soaps are then washed out with water, leaving glycerin and a methyl ester (or ethyl ester) as the resulting products. The methyl esters (or ethyl ester) serve as an efficient and clean source of diesel fuel. The glycerol, however, is damaging to diesel engines and must be removed. Biodiesel is registered with the United States Environmental Agency (EPA) as an alternative fuel for diesel engines.

This study aims to develop a new domestic biodiesel production procedure which makes use of waste fryer vegetable oil such as soybean oil by transesterification method. The waste fryer oil is derived from soybeans and is relatively abundant from food process in Taiwan. The biodiesel was esterified through the process of transesterification. Approximately 500 grams of waste fryer oil and about 300 grams of methanol are required to produce 425 grams of biodiesels (methyl ester) for an overall yield of about 85%. The transesterification process is given in Figure 1. The biodiesel and diesel fuels properties and their test methods are given in Table 2. The 20/80 and 30/70 blends of biodiesel to diesel fuel were used in this study, namely 20% blend and 30% blend respectively.

Dilution and Sampling System

The dilution and sampling system (mini-dilution system) used in these experiments was designed to give very fast dilution and cool of the exhaust with dry, clean air. Conventional dilution tunnel systems have much slower dilution processes. In roadway situations, dilution of the diesel exhaust occurs within time periods less than 1 s [14]. The sampling probe immersed and faced into the exhaust flow, followed by a short section of stainless steel tubing which is insulated. The sample then passed through insulated sample line and into the sample inlet of an ejector pump where it mixed with the dilution air. The ejector pump consisted of a compressed (dilution) air inlet, a sample inlet, and one mixture outlet. The flow through the ejector was driven

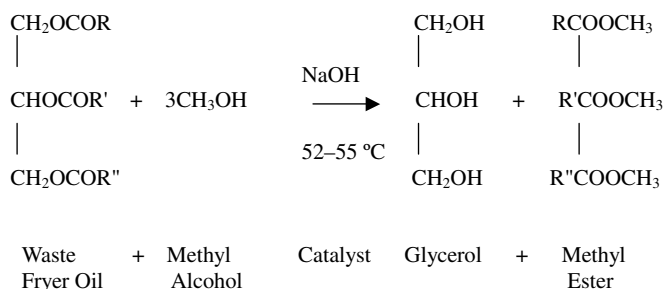


Figure 1. Waste fryer oil transesterification.

by high pressure (0.3 MPa) cool dilution air. This dilution air passed through a silica gel dryer and high efficiency particulate air (HEPA) filter to remove any incoming particles. A schematic of the mini-dilution system is given in Figure 2.

The dilution ratio (DR) of the mini-dilution system is determined by monitoring the NO_x concentration in the diluted and undiluted exhaust samples [12, 13, 19]. The dilution ratio (DR) is defined as the ratio of NO_x in the undiluted exhaust sample to the NO_x in the diluted sample (see

Table 2. Properties of Diesel and Biodiesel (Methyl Ester) Fuels and Fuel Property Test Methods

Fuel Property*	Diesel	Biodiesel
Sulfur Content, wt. % ASTM D4294	max. 0.05	max. 0.01
Flash point, °C ASTM D93	min. 52	165–190
Viscosity, cSt@40°C ASTM D445	1.91–4.1	4.31
Density, @15.5°C g/cm ³ , ASTM D1298	0.84	0.887
Cetane Index ASTM D976	min. 46	51

* Diesel properties are from Chinese Petroleum Corp's premium diesel. Biodiesel properties are based on tests performed by Exploration and Development Research Institute, Chinese Petroleum Corporation.

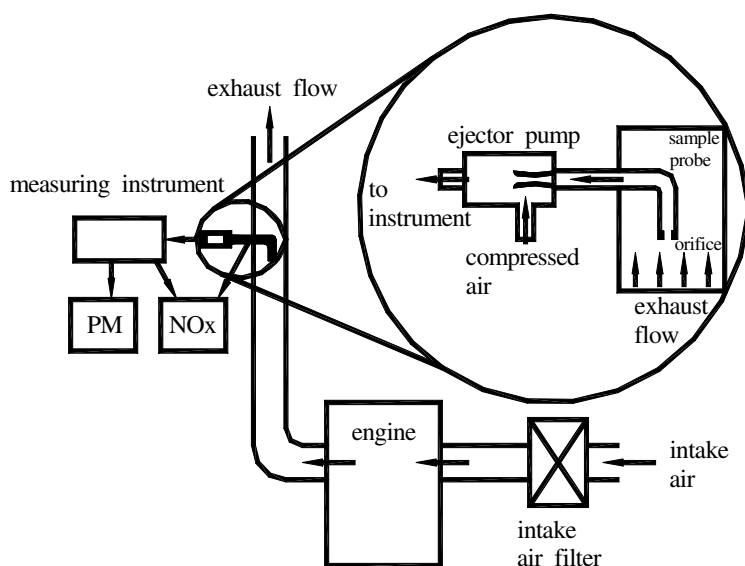


Figure 2. A schematic of the mini-dilution system.

Equation 1, where DR is the dilution ratio and N is the NO_x concentration). Dilution ratios were found to be quite stable, and were typically maintained at a ratio of approximately 10–15:1. This dilution ratio was chosen because it resulted in diluted exhaust concentrations, which were ideally suited for the dynamic range of the measurement instruments (GRIMM laser aerosol monitor) used in these experiments.

$$DR = \frac{N_{\text{NO}_x, \text{exhaust}}}{N_{\text{NO}_x, \text{diluted}}} \quad (1)$$

RESULTS AND DISCUSSION

The smoke emissions was measured for the three fuels respectively, namely 20% blend, 30% blend and diesel fuels, operated under mutually comparable condition. The data shown in Figure 3 for smoke emissions was collected by measuring the exhaust smoke opacity (%) using Bosch emission analysis measuring instrument 3.011 with opacimeter RTM 430. The test procedures followed SAE J1667, testing under free acceleration with a brief application of a specified pressure to the acceleration pedal. Load was provided by the reciprocating and centrifugal masses represented by the accelerating engine. For free acceleration, the entire test curve was recorded in digital form. The measuring instrument automatically determined the maximum value (smoke opacity %) and calculated the mean from several gas pulses.

The results showed that there was a lower smoke emissions when the engine was operated with 20% blend and 30% blend fuels. Smoke emissions decreased as the biodiesel concentration increased. The results coincide with the aforementioned studies. Smoke formation causes by high temperature decomposition, mainly takes place in the fuel-rich zone at high temperature

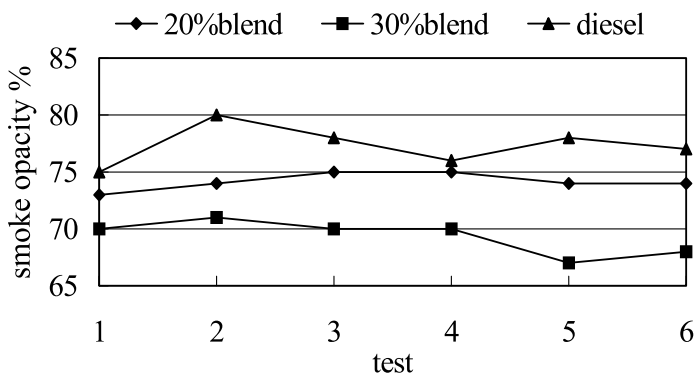


Figure 3. The influence of fuels on smoke opacity.

and pressure, specifically within the core region of each fuel spray. If fuel is partially oxygenated, it could reduce smoke emissions [20]. Because the emission of particulate matter (PM) concentration can be converted by measured smoke opacity (%) with the correlation table and alignment chart of SAE Diesel Smoke Measurement Task Force (1978), we can also deduce that PM mass emissions rate decreases as the biodiesel concentration increases. The reasons for the lower smoke emissions and PM mass emissions rate may be considered in terms of the various factors as previously stated, the dominant factor being the presence of oxygen in the biodiesel.

The gaseous exhaust emissions are measured by the ECOM-S+ emissions analyzer (for CO, NO, NO₂, and SO₂) and Bosch four-gas emissions analyzer (for HC). Measurements include CO, HC, NO, NO₂, and SO₂ emissions. The influence of engine speed and fuel type on the

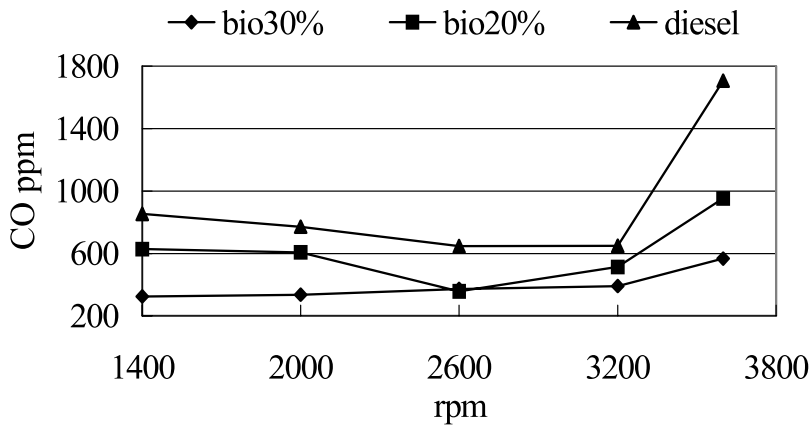


Figure 4. The influence of engine speed on CO emissions.

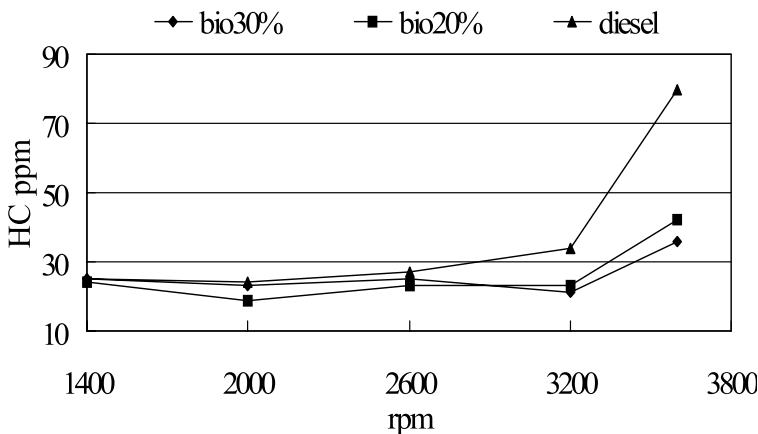


Figure 5. The influence of engine speed on HC emissions.

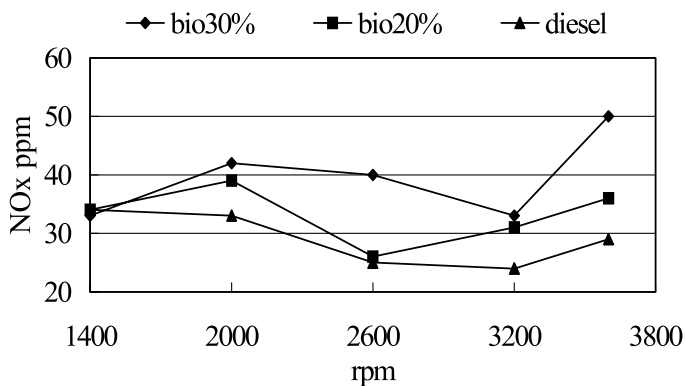


Figure 6. The influence of engine speed on NO_x emissions.

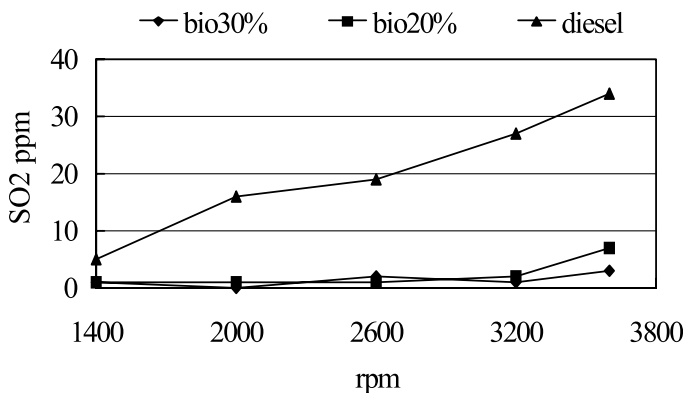


Figure 7. The influence of engine speed on SO₂ emissions.

gaseous emissions of CO, HC, NO_x, and SO₂ are shown from Figure 4 to Figure 7. The comparison between 20% blend, 30% blend and diesel fuels regarding CO emissions is given in Figure 4. CO emissions increased for the three fuels in accordance with the engine speed. The 30% blend fuel had a slow increase of CO as the engine speeded up, and the CO emissions almost remained stable (325–566 ppm) at all engine speed range (1400–3600 rpm). However, the CO emissions for diesel fuel was about 2 times those for 30% blend fuel at 1400–3200 rpm speed range, and about 3 times more at high speed (3200–3600 rpm). Whereas the CO emissions for 20% blend fuel was about 1.5 times those for 30% blend fuel at all speed range. Biodiesel blends reduce CO emissions mainly because they have a higher oxygen content than diesel, and the higher oxygen content encourages more complete combustion. This conclusion is in line with the results of the related previous studies [2, 3, 7–9, 20, 21]. We may conclude from the above comparison that biodiesel blend fuels have a lower CO emissions and better air utilization in the engine combustion chamber than diesel fuel. It has the potential to increase the

EGR (exhaust gas recirculation, a very effective method for reducing NO_x emissions) rates and hence to reduce NO_x emissions.

The comparison among 20% blend, 30% blend and diesel fuels with regard to HC emissions is given in Figure 5. The characteristics of HC emissions for the two blend fuels are completely identical. The HC emissions for the three fuels showed a steady increase as the engine speeded up. Generally speaking, biodiesel blend fuels had slightly lower HC emissions than diesel fuel at the low and medium speed range (1400–2600 rpm), whereas at the high speed range (2600–3600 rpm) biodiesel blend fuels had much lower HC emissions than diesel fuel. The results coincide with the related previous studies [2, 3, 7–9, 20, 21]. The longer carbon chains and the absence of aromatic content make cetane number of biodiesel higher than that of diesel fuel, which promotes complete combustion and reduce HC emissions [20].

The comparison among 20% blend, 30% blend and diesel fuels in relation to NO_x emissions is shown in Figure 6. Biodiesel blend fuels had a higher NO_x emissions than diesel fuel at all speed range (1400–3600 rpm), whereas the NO_x emissions of 30% blend fuel was higher than that of 20% blend fuel. On the whole, NO_x emissions increased as the biodiesel concentration increased. This is also supported by the previous studies [2, 3, 7–9, 20, 21]. The NO_x emissions higher are mainly because the biodiesel blends have a shorter ignition delay time, causing peak pressure and temperature, which enhances NO_x formation [20]. But as has been shown in the preceding findings, biodiesel blend fuels have CO emissions far less than diesel fuel, which indicates that biodiesel blend fuels have a better air utilization in the engine combustion chamber than diesel fuel, having the potential to be able to increase EGR rates substantially, and significantly reduce NO_x emissions. On the other hand, in terms of the characteristics of the fuel itself, biodiesel blends have shorter ignition delay characteristics and high cetane number which could be significantly delaying the injection timing hence to reduce NO_x emissions [6].

The comparison among 20% blend, 30% blend and diesel fuels regarding SO_2 emissions is given in Figure 7. Biodiesel blend fuels have hardly SO_2 emissions, which is due to the fact that biodiesel contains lower sulfur, while the diesel fuel used in the present experiment was Chinese Petroleum Corp's premium diesel containing sulfur $\leq 0.5\%$. Biodiesel blends therefore have a more positive contribution than diesel to the prevention from acid rain. Besides, biodiesel blends meet the requirement of current exhaust after-treatment system which regulates fuel products to contain sulfur $\leq 0.005\%$. For example, the highly active oxidation catalyst is used as low sulfur diesel fuel (sulfur content ≤ 10 wt.-ppm) [22], with regard to the relation between fuel's sulfur content and PM formation. Previous studies (Graskow et al., 1998) affirm that PM formation is hardly affected by sulfur content. The most significant parameters determining PM formation are engine load and speed.

The particle mass concentration and number concentration are measured by the GRIMM laser aerosol monitor from mini-dilution system at a variety of steady state engine speeds. A further step is then taken to look at particle number concentration (particle/liter) vs. particle size ($> 10 \mu\text{m}$, $> 5 \mu\text{m}$, $> 2 \mu\text{m}$, $> 1 \mu\text{m}$ and $> 0.5 \mu\text{m}$) at different engine speeds, for 20% blend, 30% blend and diesel fuels, respectively. From Table 3 and Figure 8 we

Table 3. Particle Number Concentration of Biodiesel Blend and Diesel Fuels at Different Engine Speeds

Fuel	$\mu\text{m}/$ rpm	1400	2000	2600	3200	3600
20% blend	> 0.5	4.53×10^5	6.41×10^5	9.43×10^5	1.35×10^6	8.44×10^6
	> 1	7.20×10^4	1.02×10^5	1.66×10^5	2.70×10^5	1.66×10^6
	> 2	5.50×10^3	1.33×10^4	2.05×10^4	3.94×10^4	2.30×10^5
	> 5	0	0	0	0	0
	> 10	0	0	0	0	0
	PM ₂	5.25×10^5	7.43×10^5	1.11×10^6	1.62×10^6	1.01×10^7
30% blend	> 0.5	1.41×10^6	2.17×10^6	3.57×10^6	3.48×10^6	1.02×10^7
	> 1	2.48×10^5	3.69×10^5	5.98×10^5	6.12×10^5	1.86×10^6
	> 2	1.97×10^4	3.86×10^4	6.33×10^4	7.23×10^4	2.64×10^5
	> 5	0	0	0	0	0
	> 10	0	0	0	0	0
	PM ₂	1.66×10^6	2.54×10^6	4.17×10^6	4.09×10^6	1.20×10^7
Diesel	> 0.5	5.88×10^5	1.08×10^6	1.40×10^6	2.32×10^6	5.46×10^6
	> 1	8.00×10^4	1.35×10^5	2.68×10^5	4.59×10^5	1.16×10^6
	> 2	5.74×10^3	1.31×10^4	3.57×10^4	6.12×10^4	1.56×10^5
	> 5	0	0	0	0	0
	> 10	0	0	0	0	0
	PM ₂	6.68×10^5	1.21×10^6	1.67×10^6	2.78×10^6	6.61×10^6

PM₂ is the summation of $> 1 \mu\text{m}$ and $> 0.5 \mu\text{m}$ particle number concentration. The unit of particle number concentration is par./liter.

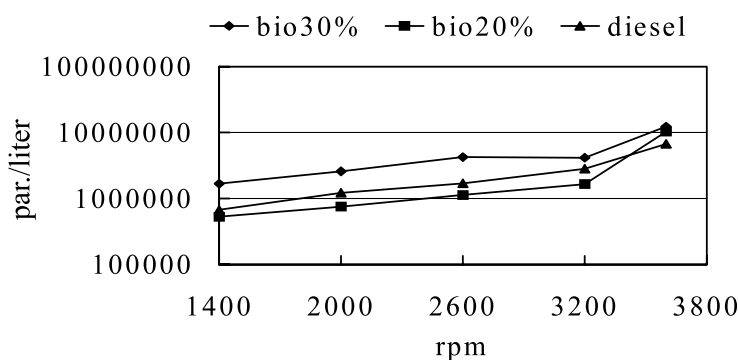


Figure 8. The influence of engine speed on PM₂ particle number concentration.

can find that $> 5 \mu\text{m}$ and $> 10 \mu\text{m}$ particle number concentration of the three fuels were zero at all engine speeds; while those of $> 2 \mu\text{m}$, $> 1 \mu\text{m}$ and $> 0.5 \mu\text{m}$ increased steadily from low to high engine speeds. With regard to the PM_2 (fine particle, the summation of $> 1 \mu\text{m}$ and $> 0.5 \mu\text{m}$ particle number concentration) particle number concentration of 30% blend was six-order at 1400–3200 rpm engine speed range, and seven-order at 3600 rpm. Its numbers tended to increase along with the increase in engine speed. On the other hand, PM_2 particle number concentration of 20% blend was six-order at 2600–3200 rpm engine speed range, five-order at 1400–2000 rpm and seven-order at 3600 rpm, whereas those of diesel fuel was six-order at 2000–3600 rpm engine speed range, and five-order at 1400 rpm. For 20% blend and diesel fuels, the PM_2 particle number concentrations also tended to increase along with the increase in engine speed. 30% blend fuel emitted PM_2 1.19 times that of 20% blend at 3600 rpm, while 2.51 ~ 3.44 times at other engine speeds; and 1.84 times that of diesel fuel at 3600 rpm, while 1.46–2.49 times at other engine speeds. On the whole, PM_2 particle number concentration of 30% blend was the highest at all engine speed range; and PM_2 particle number concentration of 20% blend was the lowest at all engine speed range with the exception of 3600 rpm. The reason remains unclear why PM_2 particle number concentration of 20% blend was about 1.54 times that of diesel fuel, particularly at 3600 rpm engine speed and about 0.58–0.79 times that of diesel fuel at 1400–3200 rpm. Nevertheless, there is no denying that generally speaking, those of the three fuels had PM_2 particle number concentration as high as above six-order and seven-order at most of the engine speed ranges. This presents a magnificent hazard to public health and the environment. We can also deduce that diesel engine fueled with biodiesel blends emit more PM_2 particle number concentration than that with diesel fuel, and PM_2 number concentration increases as biodiesel concentration increases. According to the aforementioned studies, the engine with lower PM mass emission rate while with higher particle number concentration may have the potential to significantly impact public health and the environment. This study also shows that biodiesel blends have lower PM mass concentrations than diesel, which by contrast has significantly higher fine particle number concentrations than diesel.

CONCLUSION

This study has successfully developed a new domestic biodiesel production procedure, which made of waste fryer vegetable oil such as soybean oil by transesterification method. Approximately 500 grams of waste fryer oil and about 300 grams of methanol were required to produce 425 grams of biodiesels (methyl ester) for an overall yield of about 85%.

The measured smoke emissions showed that there was a reduction of the smoke opacity when the engine was operated with biodiesel blends. Smoke emissions decrease as the biodiesel concentration increase. The CO emissions from the 30% blend operated engine are 2–3 times less than those from the diesel fuel operated engine, whereas the CO emissions for 20% blend are about 1.5 times more than those for 30% blend at all speed range. As for other gaseous emissions, such as HC, NO_x and SO₂, the results also favored biodiesel blends. Generally speaking, biodiesel blends had slightly lower HC emissions than diesel fuel at the low and medium speed range, whereas at the high speed range biodiesel blends had much lower HC emissions than those of diesel fuel. Biodiesel blends had a higher NO_x emissions than those of diesel fuel at all speed range, whereas the NO_x emissions of 30% blend were higher than those of 20% blend. On the whole, NO_x emissions increased as the biodiesel concentration increased. Besides, the biodiesel blends operated engine had hardly SO₂ emissions, hence meeting the requirement of current exhaust after-treatment system.

For 30% blend, 20% blend and diesel fuels, the PM₂ particle number concentrations tended to increase along with the increase in engine speed. On the whole, PM₂ particle number concentration of 30% blend was the highest at all engine speed ranges; and PM₂ particle number concentration of 20% blend is the lowest at all engine speed ranges with the exception of 3600 rpm. Nevertheless, those of the three fuels had PM₂ particle number concentrations as high as above six-order and seven-order at most of the engine speed ranges. This presents a magnificent hazard to public health and the environment. We can also deduce that diesel engine fueled with biodiesel blends emits more PM₂ particle number concentrations than those with diesel fuel, and PM₂ number concentration increases as biodiesel concentration increases.

REFERENCES

1. Peterson, C. L.; Thompson, J. C.; Taberski, J. S. One-Thousand-Hour Engine Durability Test with HySEE and Using a 5X-EMA Test Cycle. *Trans. of the ASAE* 1999, 42(1), 23–30.
2. Lowe, G. A.; Peterson, C. L.; Thompson, J. C.; Taberski, J. S.; Mann, P. T.; Chase, C. L. Producing Hysee Biodiesel from Used French Oil and Ethanol for an Over-The-Road Truck. *ASAE Annual International Meeting, Orlando, Florida, July 12–16, 1998*; ASAE: Joseph, 1998; Paper No. 986081.
3. Spataru, A.; Romig, C. Emissions and Engine Performance from Blends of Soya and Canola Methyl Esters with ARB#2 Diesel in a DCC 6V92TA MUI Engine. *SAE Trans.* 1995, 104, 1077–1087.
4. Dunn, R. O.; Shockley, M. W.; Bagby, M. O. Winterized Methyl Esters from Soybean Oil: An Alternative Diesel Fuel with Improved Low-Temperature Flow Properties. *SAE Trans.* 1997, 106, 640–649.

5. Ali, Y.; Hanna, M. A.; Borg, J. E. Effect of Alternative Diesel Fuels on Heat Release Curves for Cummins N14-410 Diesel Engine. *Trans. of the ASAE* 1996, 39(2), 407-414.
6. Choi, C. O.; Bower, G. R.; Reitz, R. D. Effects of Biodiesel Blended Fuels and Multiple Injections on D. I. Diesel Engines. *SAE Trans.* 1997, 106, 388-406.
7. Peterson, C.; Reece, D. Emissions Characteristics of Ethyl and Methyl Ester of Rapeseed Oil Compared with Low Sulfure Diesel Control Fuel in a Chassis Dynamometer Test of a Pickup Truck. *Trans. Of the ASAE* 1996, 39(3), 805-816.
8. Alfuso, S.; Auriemma, M.; Police, G.; Prati, M. V. The Effect of Methyl-Ester of Rapeseed Oil on Combustion and Emissions of DI Diesel Engines. *SAE Trans.* 1993, 102, 2332-2340.
9. Schumacher, L.; Borgelt, S. C.; Hires, W. G.; Wetherell, W.; Nevils, 100,000 Miles of Fueling 5.9L Cummins Engines with 100% Biodiesel. *ASAE Trans.* 1996, 105, 2332-2339.
10. Staat, F.; Gateau, P. The Effects of Rapeseed Oil Methyl Ester on Diesel Engine Performance, Exhaust Emissions and Long-Term Behavior - A Summary of Three Years of Experimentation. *SAE Trans.* 1995, 104, 1-7.
11. Hall, D. E.; King, D. J.; Morgan, T. D., B. Baverstock, S. J.; Heinze, P.; Simpon, B. J. A Review of Recent Literature Investigating the Measurement of Automotive Particulate; the Relationship with Environmental Aerosol, Air Quality and Health Effects. *SAE Trans.* 1998, 107, 1685-1695.
12. Abdul-Khalek, I. S.; Kittelson, D. B.; Graskow, B. R.; Wei, Q.; Brear, F. Diesel Exhaust Particle Size: Measurement Issues and Trends. *SAE Trans.* 1998, 107, 638-696.
13. Graskow, B. R.; Kittelson, D. B.; Abdul-Khalek, I. S.; Ahmadi, M. R.; Morris, J. E. Characterization of Exhaust Particulate Emissions from a Spark Ignition Engine. *SAE Trans.* 1998, 107, 155-165.
14. Morawska, L.; Bofinger, N. D.; Kocis, L.; Nwankwoala, A. Submicrometer and Supermicrometer Particles from Diesel Vehicle Emissions. *Environ. Sci. and Technol.* 1998, 32(14), 2033-2042.
15. Hunt, A. J.; Quinby-Hunt, M. S.; Shepherd, I. G. Diesel Exhaust Particle Characterization by Polarized Light Scattering. *SAE Trans.* 1998, 107, 1843-1850.
16. Rickeard, D. J.; Bateman, J. R.; Kwon, Y. K.; McAughey, J. J.; Dickens, C. J. Exhaust Particulate Size Distribution: Vehicle and Fuel Influences in Light Duty Vehicles. *SAE Trans.* 1996, 105, 1583-1597.
17. Greenwood, S. J.; Coxon, J. E.; Biddulph, T.; Bennett, J. An Investigation to Determine the Exhaust Particulate Size Distributions for Diesel, Petrol, and Compressed Natural Gas Fuelled Vehicles. *SAE Trans.* 1996, 105, 640-646.
18. Maricq, M. M.; Chase, R. E.; Podsiadlik, D. H.; Siegl, W. O.; Kaiser, E. W. The Effect of Dimethoxy Methane Additive on Diesel Vehicle Particulate Emissions. *SAE Trans.* 1998, 107, 1504-1511.
19. Christensen, R.; Hansen, M. B.; Schramm, J.; Binderup, M. L.; Jorgensen, V. Mutagenic Activity of the Soluble Organic Fraction of Exhaust Gas Particulate from a Direct Injection Diesel Engine. *SAE Trans.* 1996, 105, 1573-1582.

20. Wang, W. G.; Lyons, D. W.; Clark, N. N.; Gautam, M. Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification. *Environ. Sci. and Technol.* 2000, 34(6), 933–939.
21. Durbin, T. D.; Collins, J. R.; Norbeck, J. M.; Smith, M. R. Effects of Biodiesel, Biodiesel Blends, and a Synthetic Diesel on Emissions from Light Heavy-Duty Diesel Vehicles. *Environ. Sci. and Technol.* 2000, 34(3), 349–355.
22. Hawker, P.; Huthwohl, G.; Henn, J.; Koch, W.; Luders, H.; Luers, B.; Stommel, P. Effect of a Continuously Regenerating Diesel Particulate Filter on Non-Regulated Emissions and Particle Size Distribution. *SAE Trans.* 1998, 107, 37–44.

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