

Influence of Biodiesel/Diesel Blends on Particulate Emissions in a Turbocharged Common Rail Diesel Engine

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ABSTRACT

Experiments were conducted in a turbocharged, high-pressure common rail diesel engine to investigate particulate emissions from the engine fueled with biodiesel and diesel blends. An electrical low-pressure impactor (ELPI) was employed to measure the particle size distribution and number concentration. Heated dilution was used to suppress nuclei mode particles and focus on accumulation mode particles. The experiment was carried out at five engine loads and two engine speeds. Biodiesel fractions of 10%, 20%, 40%, 60% and 80% in volume were tested. The study shows that most of the particles are distributed with their diameters between 0.02 and 0.2 μm , and the number concentration becomes quite small for the particles with the diameters larger than 0.2 μm . With the increase of biodiesel fraction, engine speed and/or engine load, particle number concentration decreases significantly, while the particle size distribution varies little. The analysis on heat release rate, excess air ratio and exhaust gas temperature were provided to help interpret the particulate emissions. The study indicates that particle number concentration and mass concentration are reduced simultaneously when the engine is fueled with biodiesel/diesel blends.

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INTRODUCTION

Particulate emissions from diesel engines have received more and more attention due to their harmful effects on human health and atmospheric environment. Over the past decades, ever stricter emission standards on diesel engines lead to the significant decrease of emitted particle mass. Even though current diesel engine emission regulations have no restrictions on particle size in most countries, future regulations may require the control on the particle size distribution because of the significant impact of particle size on human health and environment. Particle size influences the atmospheric residence time of particles, the optical properties of the particles, the particle surface area and ability to participate in atmospheric chemistry, and the health effects [1]. It is believed by some that toxicity increases as particle size decreases [2, 3], therefore it is important to understand particle size and concentration of engine exhaust, and that motivates this investigation.

Due to increasing oil price and further stringent emission control regulations, the investigation on the alternative fuels has received more attention in recent years. As a clean and renewable alternative diesel fuel, biodiesel fuel has attracted great interest and become an important approach in particulate

reduction from diesel engines. Biodiesel fuels contain about 11 wt% oxygen and the oxygen in biodiesel provides an effective way to enhance combustion process and inhibit soot formation in diesel engines [4]. Moreover, biodiesel is virtually free of sulfur, which is beneficial to particulate reduction.

Previous studies showed a noticeable decrease in particulate emissions when the diesel engines were fueled with biodiesels [5, 6, 7, 8, 9, 10], although some works occasionally reported the increasing or little variation in particulate emissions [11-12]. There are also some reports on the effect of biodiesel on particle size distribution in literature [2, 6, 13, 14, 15, 16, 17]. Some studies on particle size distribution show increases in the number of small particles from the engines fueled with biodiesels [13, 14, 15]. While some other authors did not find any significant effect of biodiesel on particle sizes [2, 16-17]. Tsolakis [18] found that there was a tradeoff between the particle number and mass in a diesel engine fueled with biodiesel. The effect of biodiesel on particle size distribution is recognized to be strongly associated with engine types and operating conditions [1, 6]. By now it has begun to be recognized that the ambiguities in the scientific literature about

the effects of biodiesel on particle number emissions often arise from not distinguishing between semivolatile PM and solid particles (soot).

Up to now, most previous studies on particle size distributions fueled with biodiesel were carried out in the naturally aspirated diesel engines equipped with conventional injection system, and there were few reports on the effect of biodiesel on particle size distribution in the turbocharged, high-pressure common rail diesel engines. Some studies reported that high injection pressure promoted the generation of very large number concentrations of small particles even though the total particle mass concentration is decreased [19-20]. This effect of high injection pressure is similar to that of biodiesel in some studies [13-14], where the total number concentration is decreased and the number of small particles is increased. Therefore, it is estimated that the combination of high injection pressure and biodiesel might result in decreased particle mass concentration but increased number concentration of small particles. On the other hand, the well controlled fuel-air mixing and combustion processes in modern turbocharged, common rail diesel engines might provide the possibility in reducing both total particle number concentration and number concentration of small particles. Furthermore, it is unclear whether the reductions of particle number and mass concentration from the engine fueled with biodiesel can be achieved simultaneously in modern turbocharged, common rail diesel engines. These motivate the experimental study on particulate emissions from a turbocharged, high-pressure common rail diesel engine fueled with biodiesel and biodiesel/diesel blends.

The objective of this study is to investigate the particulate emissions in a modern turbocharged, high-pressure common rail diesel engine fueled with biodiesel/diesel blends. In order to suppress the formation of nuclei mode particles, which are mainly formed by nucleation during dilution and cooling of the exhaust, and focus on accumulation mode particles, which are mainly carbonaceous soot agglomerates and are formed directly from combustion, heated dilution was used in this study. The analysis on heat release rate, excess air ratio and exhaust gas temperature were provided to assist the analyses on the trends of particle number concentration versus fuel content and engine operating conditions.

EXPERIMENTAL SETUP AND PROCEDURES

The diesel engine in this study is a four-stroke, four-cylinder, turbocharged, high-pressure common rail diesel engine. The main engine specifications are given in Table 1. The experimental system is schematically shown in Figure 1.

The diesel engine is coupled to an eddy-current dynamometer, which is controlled by the Power-link Engine Control System (Type FC2000). The real-time engine speed, torque, and

power, as well as coolant temperature, exhaust gas temperature and lubricating oil pressure are monitored. The glow plug of the first cylinder is replaced by a Kistler piezoelectric pressure transducer (Type 6055Csp) with the same size. Cylinder gas pressure is measured by the pressure transducer with the resolution of 10 Pa. The dynamic top-dead-center (TDC) is determined under motoring operation. A Kistler's crank angle encoder (Type 2614A) is mounted on the main shaft and employed to obtain crank angle signal. Yokogawa data acquisition system DL750 is used to record to the temporal curves of cylinder gas pressure and crank angle. The signal of cylinder gas pressure is acquired with the interval of 0.1 crankshaft angle over 100 engine cycles. The averaged cylinder gas pressure is used to calculate heat release rate with the method in literature [21]. Horiba MEXA-700A instrument is employed to measure excess air ratio with an accuracy of 0.1.

Particulate number concentration and size distribution are measured with an electrical low-pressure impactor (ELPI, Dekati Ltd, Finland). This instrument operates by charging the particles in the instrument inlet by means of a unipolar positive polarity charger with subsequent separation of the particles according to their aerodynamic size in the impactor [22]. The impactor is a 13-level low-pressure impactor (including filter stage) with size levels ranging from 7 nm to 10 μ m aerodynamic diameter, as shown in Table 2. The detailed principle and process can be found in the literature [23]. To avoid overloading of the ELPI's electrometer, the exhaust gas is diluted with clean air by using a two-stage diluter (Dekati Diluter) and air compressor. Two diluters are used with constant dilution ratio of 8.43 and 8.45 respectively. Thus the total dilution ratio is 71.23. To reduce nucleation and condensation, the first diluter is heated to 200°C in advance during the experiments. Heated dilution will suppress the formation of nucleation mode particles. For the second diluter, the air is kept at ambient temperature. Dilution ratio is kept constantly for all tests to prevent the the particle distribution from changing.

Table 1. GW2.8TC engine specifications.

Type	In-line 4 cylinder, electrical controlled common rail injection, turbo-charged diesel engine
Combustion chamber	w type
Bore $\times$ stroke (mm $\times$ mm)	93 $\times$ 102
Displacement (L)	2.771
Compression ratio	17.2:1
Rated power/speed (kW/(r/min))	70 $\pm$ 3/3600
Pump	Bosch CP1H
Common rail	Bosch LWR
Injector	Bosch CR1P2, 6 $\times$ 0.137 mm

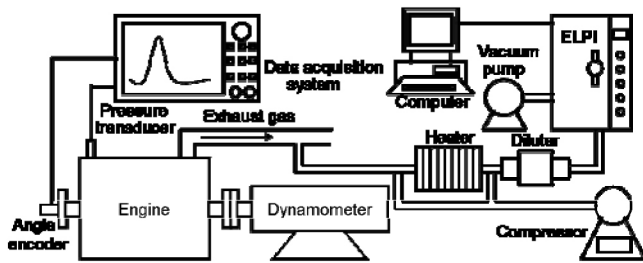


Figure 1. Schematic diagram of experimental system.

The pure fuels used are ultra-low sulfur diesel fuel (<50 ppm) and soybean-derived biodiesel. Fuel properties of diesel and biodiesel are given in Table 3. Five diesel/biodiesel blends, B10, B20, B40, B60, B80 are prepared, where BX refers to X% of biodiesel in volume in the biodiesel-diesel blends.

In this study, experiments are performed at two engine speeds of 1600 rpm and 2600 rpm. Five engine torques of 34, 68, 101, 135 and 169 Nm, corresponding to brake mean effective pressures (BMEP) of 0.154, 0.308, 0.458, 0.612 and 0.766 MPa are selected. An extended warm-up period is used until coolant reaches 80 °C. Engine speed and torque variations are maintained within ± 10 rpm and ± 0.1 Nm, respectively. Particulate measurement is conducted at steady operating conditions for 150 seconds. During the steady operation, cylinder pressure and crank angle are recorded simultaneously.

Table 2. ELPI specifications.

Impactor level	D50% (μm)	D_i (μm)	Width (dlogDp)
1	0.007	0.0208	0.6021
2	0.028	0.0392	0.2932
3	0.055	0.0715	0.2281
4	0.093	0.1208	0.2274
5	0.157	0.2036	0.2257
6	0.264	0.3188	0.1639
7	0.385	0.4874	0.2048
8	0.617	0.7672	0.1893
9	0.954	1.2393	0.2273
10	1.610	1.9657	0.1734
11	2.400	3.1061	0.2240
12	4.020	6.3308	0.3945

Table 3. Physical and chemical properties of diesel and biodiesel.

	Diesel	Biodiesel
Low heating value (MJ/kg)	43.1	37.4
Density (kg/m ³)	840	881.5
Viscosity (mm ² /s)	3.4	4.27
Cetane number	53	51.5
Carbon content (wt%)	86.1	77.1
Hydrogen content (wt%)	13.8	11.8
Oxygen content (wt%)	0	10.9

RESULTS AND ANALYSIS

Figure 2 (in Appendix) shows the exhaust particle number size distributions (corrected for dilution ratio) for different fuels. The abscissa for particle size is plotted in the logarithm scale. The size distribution curves are unimodal, and lognormal pattern for all fuels and operation conditions. The peak values of particle number concentrations appear at 0.039 μm . Most of the particles are distributed with their diameters between 0.02 to 0.2 μm . Number concentration becomes quite low for the particles with diameters larger than 0.2 μm .

As the engine speed increases from 1600 rpm to 2600 rpm under a specific engine load, the particle number concentrations decreases noticeably especially under high engine loads. This can be deduced from the sharply decreased peak values in number concentrations at engine speed of 2600 rpm. The size distributions show little variation with engine speed. The decreased particle number concentration and almost unchanged size distribution with increasing engine speed are different to those of previous studies [13, 14, 15]. This trend is considered to be strongly associated with the engine configuration. Fuel air mixing process and combustion in the combustion chamber is responsible for this behavior. This will be discussed in details in the late discussion section.

As shown in Figure 2 (in Appendix), the particle number concentration decreases with the increase of engine load. As similar to engine speed effect, this trend is also different to the results in most of previous studies [15, 18], where the increased particle number concentration with increasing engine speed and/or load was attributed to the increased amount of burned fuel mass and the decreased excess oxygen in combustion. Lapuerta et al. [24] suggested that at high engine load, due to the increased fuel injected, combustion took place with the decreased excess oxygen, which coupled with higher pressure and temperature in the combustion chamber, contributed to soot nucleation and promoted the growth of the existing soot nuclei. Moreover, particle number concentrations are strongly associated with engine types [1]. The fuel-air mixing and combustion process in this turbocharged, high-pressure common rail diesel engine would be different to those in the conventional diesel engines. This results in the different trends of particle number concentrations to engine speed and load among different engine types.

The results show that particle size distributions for different fuel blends are almost the same. The diesel engine can remarkably decrease particle number concentration as biodiesel is added in diesel. With the increase of biodiesel in the blends, the reduction of carbon content and increase of oxygen content are favorable to reduce soot nuclei and hence particle number concentration. Chen and Wu [2] tested a single-cylinder engine under three-steady modes and reported no significant difference in the particle size distribution between diesel and soybean-oil biodiesel fuels, and they also found that the number of emitted particles is decreased by 30-49% with soybean biodiesel. Their results are similar to those from this study.