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Particle emissions from biodiesels with different physical properties and chemical composition

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HIGHLIGHTS

- Four biodiesels were used to investigate their influence on particle emissions.
- Particle emission increased with the increase of biodiesel carbon chain length.
- Particle emissions reduced consistently with fuel oxygen content.
- Particle median size found dependent on the type of fuel used.
- Biodiesel chemical composition found more important than physical properties.

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ABSTRACT

Biodiesels produced from different feedstocks usually have wide variations in their fatty acid methyl ester (FAME) so that their physical properties and chemical composition are also different. The aim of this study is to investigate the effect of the physical properties and chemical composition of biodiesels on engine exhaust particle emissions. Alongside with neat diesel, four biodiesels with variations in carbon chain length and degree of unsaturation have been used at three blending ratio (B100, B50, B20) in a common rail engine. It is found that particle emission increased with the increase of carbon chain length. However, for similar carbon chain length, particle emissions from biodiesel having relatively high average unsaturation are found to be slightly less than that of low average unsaturation. Particle size is also found to be dependent on fuel type. The fuel or fuel mix responsible for higher PM and PN emissions is also found responsible for larger particle median size. Particle emissions reduced consistently with fuel oxygen content regardless of the proportion of biodiesel in the blends, whereas it increased with fuel viscosity and surface tension only for higher diesel–biodiesel blend percentages (B100, B50). However, since fuel oxygen content increases with the decreasing carbon chain length, it is not clear which of these factors drives the lower particle emission. Overall, it is evident from the results presented here that chemical composition of biodiesel is more important than its physical properties in controlling exhaust particle emissions.

1. Introduction

Compression Ignition (CI) engines are increasing in popularity due to their higher thermal efficiency. They power a wide range of land and sea transport as well as provide electrical power, used in farming, construction and industrial applications. Tail pipe emissions of diesel engines, especially particulate matter (PM) are still a matter of concern due to its harmful effects both on human health and the environment [1,2]. Exposure to diesel particulate matter (DPM) can cause pulmonary diseases such as asthma, bronchitis and lung cancer [1] and because of these adverse effects, the International Agency for Research on Cancer (IARC) included DPM as carcinogenic to human health.

The harmful effects caused by DPM are related to both the physical properties and chemical composition of the particles. The physical properties that influence respiratory health include parti-

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cle mass, surface area, mixing status of particles, number and size distribution [3]. The particles deposit in different parts of the lung depending on their size. The smaller the particles the higher the deposition efficiency [4] and the greater the chance of them penetrating deep into the lung. The smaller particles stay suspended in the atmosphere for longer thus have a higher probability of being inhaled and consequently deposited deep in the alveolar region of the lung. Particle number governs the ability of particles to grow larger in size by coagulation while particle surface area determines the ability of the particles to carry toxic substances. Recent studies reveal that DPM surface area and organic compounds play a significant role in initiating various cellular and chemical processes responsible for respiratory disease [3,5]. In addition to this, a large fraction of DPM is black carbon, which is considered the second most potential green house warming agent after carbon dioxide [2]. After treatment devices (ATD) like diesel particulate filters (DPF) and diesel oxidation catalysts (DOC) aid in reducing DPM [6]. Alternative fuels are another potential emission reducing source [7]. Of these fuels, biodiesel is considered one of the more promising for diesel engines [8,9] as it produces less PM and other gaseous emissions [9–11]. Biodiesel in diesel engines also has the potential to neutralize carbon emissions as it comes from a renewable source of energy.

Biodiesel is a mixture of fatty acid esters with physicochemical properties that mostly depend on the structure of the ester molecule. They can be produced from a variety of feedstock sources such as vegetable oil, animal fat, municipal and industrial waste and some even from insects [12–15]. The vast majority of feedstocks actually used now days are derived from vegetable oils and animal fats. An extensive range of fatty acid profiles exist among these feedstocks [16], with fatty acid profiles being even different within the same feedstocks. If plant sources are used, these variations can be controlled by manipulating stock growing conditions. Physical properties and chemical composition of biodiesel varies among different feedstocks, which can have a noticeable influence on engine performance and emissions [17]. McCormick et al. [18] reported constant PM emissions from different biodiesel feedstocks when the density was less than 0.89 g/cm^3 or cetane number was greater than about 45, but increase of NOx emissions with the increase of biodiesel density and iodine number. In contradiction to these findings, a difference in particle emissions from biodiesel from different feedstocks has also been reported [19,20]. Lapuerta et al. [10] reported a 10% increase of NOx and 20% decrease of particle emissions by unsaturated biodiesel. Benjumea et al. [21] found that the degree of unsaturation in biodiesel does not significantly affect the engine performance but increases smoke opacity and THC emissions. Karavalakis et al. [22] reported noticeable influence of biodiesel origin on particle emissions, especially particle associated PAH and carbonyl emissions. Very recently Salamanca et al. [23] reported increased PM and HC emissions from biodiesel that contains more unsaturated compounds that favor soot precursor formation. There is no distinction however in the literature, which indicates whether chemical composition of biodiesel, physical properties or a combination of these is responsible for this variation in engine performance and emissions. This study therefore, aims to investigate the effect of biodiesel physical properties and chemical composition on engine exhaust particle emissions. It is an extension of the previous study [24] where results from the same experiments were presented for the engine performance characteristics and emission of pollutants including some preliminary results for the particle emission, particularly for pure biodiesel. It should be noted that the results for B100 are reproduced here for comparison purposes. Furthermore, the paper elaborates on these findings and presents new analysis in terms of the physical properties chemical composition of the fuels and their blends.

2. Materials and methods

2.1. Engine and fuel specification

This experimental study was performed in a heavy duty 6 liters, six cylinders, turbocharged after cooled, common rail diesel engine typically used in medium size trucks. Test engine is the same as used in Pham at el. [24]. Table 1 shows specification of the test engine. The engine was coupled to a water brake dynamometer, and both of them are connected to an electronic control unit (ECU). Engine was operated at 1500 rpm (maximum torque speed) and at 2000 rpm (intermediate speed), and four different loads including 25%, 50%, 75%, and 100% for each engine speed. Maximum load at any particular engine speed depends upon the type of fuel used. Therefore, for each fuel maximum load was measured at first when engine was in full throttle for a particular speed. This measured load is then considered as 100% load for that speed and other load conditions were determined based upon measured 100% load. Although PM emissions can be quiet different for transient testing, we had to conduct steady state tests as most of our measurement techniques required steady emission over longer sampling time.

An ultra low sulfur diesel (sulfur content 2.5 mg/kg) and four biodiesels with different physical properties and chemical composition were used to run the engine. All four biodiesels originated from palm oil that was then fractionated to separate its fatty acid ester components with specific composition. Since all of them have originated from the same feedstock, the given code names (C810, C1214, etc.) are to indicate the carbon chain length of the most abundant FAME. For example C810 means biodiesel that is mainly composed of FAME's with 8–10 carbon atoms. All four biodiesels were used at three blending ratios i.e. 100% biodiesel (B100), blends of 50% diesel and 50% biodiesel (B50), and blends of 80% diesel and 20% biodiesel (B20). Table 2 shows the fatty acid profile of used biodiesels as found using gas chromatography mass spectrometry (GCMS) analysis. Biodiesel samples were analyzed using Perkin Elmer clarus 580GC-MS equipped with Elite 5MS 30 m × 0.25 mm × 0.25μm column with a flow rate of 1 mL/min. Before analysing, each biodiesel was diluted with *n*-hexane (1:100 v/v). Initial temperature was 120 °C for 0.5 min, then raised to 310 °C for 2 min at 10 °C/min and kept at 310 °C for 2 min. The mass selective detector was optimized using calibrating standards with reference masses at m/z (40–350). Among four biodiesels, C810 is fully saturated and composed of 52% and 46% caprylic acid and capric acid ester respectively. C1214 is also dominated by saturated compounds but has comparatively longer carbon chain length fatty acid ester i.e. 48% lauric, 19% myristic, 10% palmitic and 18% oleic acid ester. On the other hand both C1618 and C1822 are dominated by long chain unsaturated fatty acid esters. C1618 is composed of 21% palmitic, 9% stearic, 58% cis-oleic and 10% linoleic acid ester where C1822 has 10% more oleic and linoleic

Table 1
Test engine specification,

Model	Cummins ISBe220 31
Cylinders	6 in-line
Capacity (L)	5.9
Bore × Stroke (mm)	102 × 120
Maximum power (kW/rpm)	162/2500
Maximum torque (Nm/rpm)	820/1500
Compression ratio	17.3
Aspiration	Turbocharged & after cooled
Fuel injection	Common rail
After treatment systems	None
Emissions certification	Euro III

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