Fuel 165 (2016) 413–424

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Assessment of particulate matter in exhaust gas for biodiesel and diesel under conventional and low temperature combustion in a compression ignition engine

Yongjin Jung, Joonsik Hwang, Choongsik Bae *

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

HIGHLIGHTS

- Particulate matter from waste cooling oil biodiesel was investigated.
- Particulate matter in conventional and low temperature combustion (LTC) was compared.
- Biodiesel particulate matter in LTC showed significant mass reduction from 200 to 420 °C.
- Weight fractions of hydrogen and oxygenated content are relatively large in the LTC mode.

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 6 October 2015
Accepted 19 October 2015
Available online 24 October 2015

Keywords:
Waste cooking oil (WCO) biodiesel
Soot
Particulate matter (PM)
Low temperature combustion (LTC)
Thermogravimetric analysis (TGA)

ABSTRACT

Particulate matter (PM) from the exhaust gas of a single-cylinder direct-injection compression-ignition engine was investigated by thermogravimetric analysis (TGA), elemental analysis, and transmission electron microscopy (TEM). Two fuels were used: biodiesel derived from waste cooking oil and commercial diesel fuel. Exhaust gas recirculation was applied to implement low temperature combustion (LTC), and the PM emissions of LTC were compared to those of conventional compression ignition combustion. TGA showed that significant mass reduction occurred at a temperature range of 200–420 °C for biodiesel PM in the LTC mode due to desorption of the volatile organic fraction; diesel PM from the conventional combustion mode shows the highest resistance to the desorption within the entire temperature range. Elemental analysis revealed that the weight fractions of hydrogen and oxygen content, of which the volatiles are comprised, are much larger in the LTC mode than the conventional mode. The exposed surface area after the desorption of volatiles and the oxygen group may result in the fast oxidation of biodiesel PM. Particulate matter in the conventional combustion mode contains a large portion of carbon species, in contrast to the LTC mode. The carbon content in diesel PM from conventional combustion could be due to carbonaceous soot particles, because TEM images appeared to be of a highly ordered structure. Using a scanning mobility particle sizer, fewer particles were found to be of the accumulation mode with LTC engine operation than in the conventional combustion mode, which is consistent with the observed low level of smoke emission.

1. Introduction

Biodiesel from vegetables has drawn our attention in the past decades, because it can be used in compression ignition engine. In addition, the renewability of biodiesel could make it relatively sustainable, in view of the limited supplies of fossil fuel. However, with regard to edible food, the resort to biodiesel derived from sugarcane and vegetable oils such as soybean oil has a potentially detrimental effect since the scarcity of food worldwide has grown. Waste cooking oil (WCO) biodiesel can help alleviate the issue of edible food use, as well as the disposal of waste oil by recycling. The cost competitiveness that is gained by the reuse of a waste product is supportive of efforts to use WCO biodiesel as an alternative fuel for compression ignition engines [1,2]. WCO biodiesel, as well as foodstuffs biodiesel, can reduce the soot particles in exhaust gas because the oxygen content in the fuel molecule is related to the reduced carbon availability for the soot inception process [3–6]. Fuel passage in an injector can coke significantly with biodiesel, leaving deposits that can bring about wear [7]. Even though the

---

* Corresponding author. Tel.: +82 42 350 3044; fax: +82 42 350 8820.
E-mail address: csbae@kaist.ac.kr (C. Bae).

http://dx.doi.org/10.1016/j.fuel.2015.10.076

application of biodiesel to conventional compression ignition engines has disadvantages such as the wear issue, the lower heating value and the higher viscosity [8], biodiesel has been demonstrated as a promising alternative fuel for compression-ignition engines.

Low temperature combustion (LTC) can be implemented by reducing the oxygen concentration using a large amount of exhaust gas recirculation (EGR) and advanced injection timing than for conventional running conditions to prolong the ignition delay while allowing a partially premixed charge [9,10]. The recirculated gases enter the intake, where a portion of the fresh air is replaced by carbon dioxide (CO_2) and water (H_2O) from the exhaust gas, has thermal, dilution, and chemical effects [11]. Substances with higher heat capacity such as CO_2 and H_2O lower the in-cylinder temperature [9]. Consequently, certain hazardous emissions such as nitrogen oxides (NOx) and particulate matter (PM) are produced in lower concentrations due to the low combustion temperature. Although hydrocarbons (HC) and carbon monoxide (CO) are hard to oxidize due to low combustion temperature, the low temperature combustion can be a promising technology to reduce NOx and PM simultaneously.

In a compression ignition engine, the two general methods for implementing LTC are homogeneous-charge compression-ignition (HCCI) combustion, and combustion with a high rate of EGR. HCCI combustion achieves a low combustion temperature via a lean-burn; combustion with a high EGR rate causes the combustion temperature to be lowered by reducing the oxygen concentration at the intake. Hereafter, it is the latter refers to as LTC.

When compared with that emitted from conventional compression-ignition (CI) combustion, PM from the LTC regime showed disordered structure and the size distribution of aggregates shifted to a smaller diameter range [12–15]. The process of oxidation of soot particles from LTC showed a relatively high oxidation rate [16]. In this paper, soot oxidation refers not to high temperature oxidation during the combustion process but to the oxidative reaction that usually occurs in a particle trap. Particulate matter is assumed to contain carbonaceous soot particles, as well as volatile organic fractions that is usually derived from the unburned fuel, lubricant, and species from the fuel–air reaction.

The formation of particulate matter is also significantly related to engine load conditions [17–20]. Using transmission electron microscopy (TEM), we found that soot particles from low-load conditions appeared to be of a transparent amorphous structure consisting of isolated spherules, or small aggregates formed of a few primary particles [18,21]. These intrinsic characteristics have been found in PM from laboratory burner flames, particularly in the lower region of a laminar diffusion flame [22,23]. The inverse diffusion flame, where the fuel and oxidizer are switched, was used to study the immature soot particles residing at the early stage of soot formation due to the absence of an abrupt carbonization process [22,24,25].

Biodiesel soot oxidation is characterized by a fast oxidative reaction and internal burning. The oxidation of biodiesel soot is accelerated by removal of the outer shell layer due to desorption of the surface oxygen group in the opened edge sites [26]. Once the core has internal burning, the oxidation process becomes an even faster progress with a layer rearrangement [27]. When EGR is applied, the surface area revealed by the evaporation of volatiles is related to the entire oxidation procedure [16]. However, the effect of the removal of the volatiles has not been investigated. In addition, PM in the LTC mode with biodiesel fuel can contain a larger organic fraction than conventional CI combustion fueled with diesel fuel [13]. The study of the organic fraction of PM can provide particular importance for practical purposes.

This work aims at revealing the variations in the oxidation (including desorption) process, composition and morphological characteristics of particulate matter fueled with conventional diesel and WCO biodiesel under the several operating conditions. Since the amount of the volatiles can affect the PM desorption and oxidation characteristics as described above, the WCO biodiesel PM is expected to exhibit different characteristics. In addition, LTC was chosen as an operating condition under which to investigate particulate matter with condensed hydrocarbons having a high proportion of volatiles, for comparison with outcomes under conventional CI combustion conditions. Thermogravimetric analysis was performed to investigate the desorption and oxidation process effectively, because the volatiles and soot particles show different behaviors depending on temperature of the carrier gas. The composition of the particulate matter was also studied as weight fractions by elemental analysis, which can decompose the sample into C, H, O, N, and S species. Differences in morphology can be expected with respect to the operating conditions and fuel formulation, thus transmission electron microscopy was employed. The primary particle diameters were measured using the TEM images, and the aggregate sizes were measured using a scanning mobility particle sizer (SMPS).

2. Experimental setup

The test engine was a single cylinder direct injection compression ignition engine with a bore of 100 mm, stroke of 125 mm, displacement of 980 cm^3, and compression ratio of 17.4. The specifications of the engine are summarized in Table 1. It was equipped with a high-pressure common-rail injection system. Commercial diesel fuel and waste cooking oil biodiesel were supplied to a common-rail system through a fuel filter, and the pressure was adjusted by a pressure controller (Zenobalti Co.; ZB-1200). The injection timing, as well as the duration, was controlled by a programmable signal driver (Zenobalti Co.; ZB-5000), and the command signal for the injection was synchronized by a cyclic encoder for 1800 pulses a revolution (Autonics, E50S8). The injector has 8 nozzle holes with the nominal diameter of 0.131 mm, respectively. Engine speed was consistently controlled by a DC dynamometer (82 kW). Naturally aspirated air was introduced to an intake surge tank to settle fluctuations. The ambient air and coolant temperature were kept at 25 °C and 80 °C, respectively. Low temperature combustion was implemented by using a large amount of EGR, up to 60%, and exhaust gas was passed through an exhaust surge tank whose output was merged into the intake stream. The amount of EGR was controlled by a three-way valve, and the rate was calculated by the volume ratio of carbon dioxide content in the intake to that of the exhaust, as shown in Eq. (1). Fig. 1 shows a schematic diagram of the experimental apparatus.

$$\text{EGR rate } (\%) = \frac{[CO_2]_{\text{intake}}}{[CO_2]_{\text{exhaust}}} \times 100 \tag{1}$$

The in-cylinder pressure was acquired by a piezoelectric transducer (Kistler, 6052C) every crank angle (CA) of 0.2°, and averaged for 100 cycles to calculate the heat release rate (HRR). The in-cylinder pressure trace and HRR are presented in Fig. 2.

Table 1
Specifications of the engine.

Item	Specification
Number of cylinder	Single
Injection system	Common-rail direct injection
Valves per cylinder	4 (2 intake and 2 exhaust)
Cycle	4 stroke
Bore (mm)	100
Stroke (mm)	125
Displacement (cm^3)	980
Compression ratio	17.4:1