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Combustion characterization of waste cooking oil and canola oil based biodiesels under simulated engine conditions

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ABSTRACT

Alternative fuels will come from a variety of feed stocks and refinement processes. Understanding the fundamentals of combustion and pollutants formation processes of these fuels will be useful for their implementation in different combustion systems. In this work, optical diagnostics were performed to waste cooking oil (WCO) and canola oil (CAO) based biodiesel sprays to assess their combustion and soot formation processes. Conventional diesel was used as a reference fuel for comparison with the biodiesels. The experiments were conducted in an optically-accessible constant-volume combustion chamber (CVCC) with simulated compression-ignition engine conditions, with different degree of exhaust gas recirculation. The liquid length and lift-off length results indicate that there was no significant interaction between the liquid phases of the fuels and their combustion regions. The flame lift-off lengths were found to be affected by both the chemical and physical properties of the fuels. It was observed that a larger difference between the lift-off length and the first-luminosity distance was correlated with lesser downstream soot formation, although the molecular structure of the fuel was found to affect the process too. Assessing the sooting and combustion characteristics of the biodiesel and diesel flames across the varied ambient O_2 atmospheres revealed that the estimated soot contents of the biodiesel and diesel flames peaked at 15 and 21 vol.% O_2 concentration, respectively. The peak soot contents of the WCO and CAO biodiesel flames were found be comparable, but lower than that of diesel, across the various O_2 environment. The results also demonstrated that the biodiesels have higher normalized peak pressure values than diesel at all O_2 conditions. Two-color pyrometry data demonstrated that the measured soot temperature and soot KL factors of the flames were similar at 15 and 21 vol.% O_2, but varied with further reduction of ambient O_2 concentration. Variations in the combustion duration and flame area were found to be fuel dependent.

1. Introduction

Diesel–fueled compression-ignition engines are becoming increasingly popular choice for ground transport vehicles because of their high torque output and fuel efficiency. However, particulate emissions from diesel engines, which can profoundly affect human health and environment [1,2], remain a major concern. Using alternative diesel fuels, such as biodiesels, is widely considered to be a promising method to control particulate emissions from compression-ignition engines during combustion. The oxygen content of biodiesel fuels have been reported to provide an effective route to enhance combustion and to inhibit soot formation in compression-ignition engines [3,4]. This has motivated many research and development activities, ranging from the modifications of the upstream cultivation process to enhance feedstock production for biofuels [5], down to the detailed study of combustion and emission characteristics of biodiesel fuels in the diesel engines [3,6] over the past decades. Table 1 presents a summary of selected experimental investigations involving combustion diagnostics of biodiesels in optically-accessible combustion chambers that are relevant to this work, as an example of the quantity of fundamental studies performed in this subject area.

Despite the many previous studies, the impact of the properties of the biodiesel fuels on soot emissions remain only vaguely known due to the multitude and complexity of the associated processes. In addition, biodiesels are mixtures of fatty acid methyl esters (FAMEs) with different chain lengths and degrees of saturation, which can vary

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Table 1
Summary of selected experimental conditions involving investigations of biodiesels in combustion chambers cited in this work.

Fuels	Combustion ambient test conditions	Injection specifications	Reference
Diesel, JP-8, world average Jet A blend, Fischer–Tropsch fuel, coal-derived fuel, surrogate fuel	6–6.7 MPa 900–1000 K, 15% O_2 concentration	Single-hole 0.09 mm hole diameter 150 MPa injection pressure	[13]
Butanol, soybean biodiesel	3.3–4.2 MPa, 800–1000 K, 21% O_2 concentration,	Six hole, 0.145 mm hole diameter, 134 MPa injection pressure	[43]
Diesel, soybean biodiesel, ethanol, n-butanol	2.9–4.2 MPa, 700–1000 K, 21% O_2 concentration,	Six hole, 0.145 mm hole diameter, 134 MPa injection pressure	[46]
Diesel, soybean biodiesel	2 MPa, 873 K, 9.6–20.8% O_2 concentration	Six hole, 0.1 mm hole diameter, 100 MPa injection pressure	[39]
Diesel, soy methyl ester	6–6.7 MPa, 900–1000 K, 15% O_2 concentration,	Single-hole, 0.9 mm hole diameter, 150 MPa injection pressure	[32]
JIS# Diesel, palm oil biodiesel, cooking oil biodiesel	4 MPa, 885 K, 21% O_2 concentration	Single-hole, 0.16 mm hole diameter 100–300 MPa injection pressure	[14,52]
Diesel, soybean biodiesel	2 MPa, 800–1200 K, 15–21% O_2 concentration	Six hole, 0.145 mm hole diameter, 100 MPa injection pressure	[16]
Diesel, waste cooking oil biodiesel	3.5–5.3 MPa, 800–1200 K, 21% O_2 concentration	Six hole, 0.152 mm hole diameter, 100 MPa injection pressure	[20,22]

significantly depending on their feedstocks [7,8]. Such variations can have a complicated impact on biodiesel atomization, evaporation, combustion and soot formation processes, and hence, the ensuing engine performance [4,8]. The lack of control of all of these factors have led to contradictory results being reported in the literature. For instance, many studies have reported that fuels with higher cetane numbers have shorter ignition delays, which would therefore lead to an increased soot formation due to insufficient fuel-ambient mixing before the onset of combustion [9]. Nonetheless, there are other studies that show reduction in soot and unburned hydrocarbon emissions, when fuels of high cetane number values were used [10,11]. The differences are likely to be attributable to molecular structure effects of the fuels used. In addition, in a previous study conducted by Pham et al. [12], it was reported that the oxygen content in biodiesels would contribute towards particle formation suppression in the premixed spray combustion zone, and increased particle oxidization at the flame front. In a separate study that was conducted by Park et al. [9], however, it was demonstrated that the soot formation is mainly controlled by the fuel–air mixing process for fuels with similar amount of oxygen within the fuel, and number of carbon–carbon bonds. These findings demonstrate the difficulties in drawing conclusions from a change to a single fuel property, which could simultaneously impact on other fuel properties [13]. The complexities that arise from the inter coupling between the various fuel properties produce some degree of uncertainty as to which effect would have a greater impact on the soot formation process of the flame [14].

Engine operating parameters, such as fuel injection pressure and exhaust gas recirculation (EGR), can have a pronounced impact on the combustion and pollutant formation processes of the fuel in compression-ignition engines. High pressure fuel injection, for example, could be used to improve spray atomization and combustible mixture preparation, which can lead to reduced particulate emission and improved engine performance [14,15]. The introduction of EGR can result in low temperature combustion (LTC) condition, which can lead to reduced NOx emissions [16] from compression ignition engines. The effects of these varied operating parameters on the engine and emission performances, however, can also change significantly depending on the fuel type used. For example, it has been reported that increasing injection pressure can potentially lead reduced flame residence time available for fuel elements to undergo soot formation [17], in addition to the general consensus that it can help improve the atomization and vaporisation processes of a fuel. Nonetheless, other studies have also demonstrated that high fuel injection pressure can lead to wall-wetting, which would result in increased engine-out emissions of uHC, CO and smoke [18]. The wall-wetting issue is generally more problematic when biodiesels are used, as they typically have longer spray penetrations due to their higher fuel densities when compared with diesel [19]. In addition, in a previous work that was conducted by Zhang et al. [20], it was reported that the effects of EGR may vary depending on the fuels such that a lower oxygen-concentration environment was necessary for diesel to achieve a higher combustion efficiency and lower soot emission, when compared with biodiesels. All these highlight the need to perform a direct assessment the effects of common engine operating parameters on the combustion and pollutant emission processes for the biodiesel fuel of interest, to ensure efficient and clean engine operation when used.

This work is therefore aimed at assessing the combustion properties of biodiesels from the transesterification of waste cooking oil (WCO) and canola oil (CAO) under simulated compression-ignition engine conditions in a constant-volume combustion chamber (CVCC). The WCO biodiesel is specifically targeted as it is the main biodiesel feedstock in Australia [21]. The CAO biodiesel is also selected for study as it has been extensively investigated by the authors under open flame burner and performance engine settings [12], in addition to having fuel properties that are similar to the WCO biodiesel, and is therefore useful for comparison. Optical diagnostic techniques, including OH chemiluminescence and high-speed flame natural luminosity imaging, are used to assess the impact of these varied parameters both on the air entrainment rate occurring upstream of the lift-off length, and on the downstream soot formation and combustion processes of the biodiesel jet flames. The two-color pyrometry technique is applied to the recorded flame natural luminosity images to provide soot temperature