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Soot formation in diffusion oxygen-enhanced biodiesel flames

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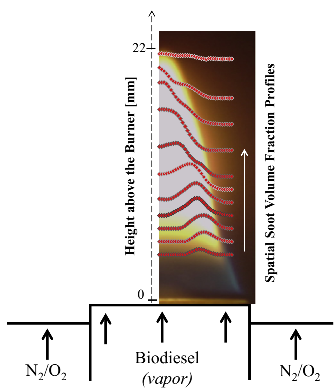
HIGHLIGHTS

- Obtained soot volume fractions of flames formed with CME and SME fuels.
- Examine the effect of biodiesel/diesel blending ratio on soot formation in flames.
- Study soot formation in CME/SME flames by varying oxygen content in the oxidizer.
- A slight increase of oxygen content increases soot population by several folds.
- Further increasing oxygen content in the oxidizer stream suppressed soot formation.

GRAPHICAL ABSTRACT



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ABSTRACT

The focus of this work is the experimental investigation of soot formation in coflow flames formed of two fatty acid methyl esters (FAMEs) by employing the light extinction/scattering technique. Three different sets of experiments were conducted in this study. In the first set, radial soot volume fraction (f_v) profiles of flames of vaporized neat canola methyl ester (B100CME) and neat soy methyl ester (B100SME) fuels both using air as the oxidizer were obtained. In the second set of experiments, the effect of oxygen content in the oxidizer stream on soot formation was studied in both FAME formed flames by increasing the oxygen content in the oxidizer stream from 21% to 35%, 50% and 80%. In the third set of experiments, the effect of fuel blending on the formation of soot particulates was studied in flames formed using CME blended with No. 2 diesel. The blends consisted of 80% biodiesel/20% diesel (B80) and 50% biodiesel/50% diesel (B50). The flames were scanned in the radial direction at various heights above the burner (HAB). For the B100CME-air flame the measured soot volume fraction f_v peak was 4.04 ppm and was located at the symmetry axis at a HAB of 16.25 mm. For B100SME-air, the f_v peak was measured to be 4.22 ppm at approximately the same flame height as in the CME-air flame. For the B100CME oxygen enriched-air flames the peak values at 35%, 50% and 80% were 6.50, 5.82 and 3.22 ppm, respectively. It was observed that by increasing the oxygen content in the B100CME flame from 21% to 35% oxygen, the f_v peak increases by approximately 61%. However, a further increase in oxygen content in the oxidizer stream suppressed soot formation. A similar trend in the f_v was observed for B100SME oxygen-enhanced flames. Furthermore, the increase of diesel fuel in the blending of B50CME resulted in significantly higher f_v values compared to the B80CME. The addition of oxygen content in the oxidizer stream in these blended fuel flames (from air to 35%) resulted in an increase in the f_v peak of approximately 47% and 71%, respectively. Centerline temperatures were measured at various HAB for selected flames.

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1. Introduction

Biodiesel (BD) has the potential to significantly address environmental concerns by reducing greenhouse gas emissions, interrupt the dependence on petroleum-based fuels and tremendously contribute to the local economy. A biodiesel fuel (BDF) which can be prepared from vegetable oils and animal fats is considered a clean, biodegradable and renewable fuel and potentially the best alternative to petroleum-based fuel. BDF is defined as a mixture of mono-alkyl esters of long-chain (C16–C18) fatty acids, usually methyl esters, obtained by the transesterification of the triglycerides contained in vegetable oils and animal fats [1]. Today, petroleum-based fuels meet 36% of U.S. energy demand [2] with 70% directed to fuels used in transportation including gasoline, diesel and jet fuel. Diesel fuel is predominantly used by light to heavy-duty trucks [3] and due to its high aromatics content, it is responsible for massive particulate matter emissions in the flue gases, which in turn trigger major health and environmental issues. The application of BD and biodiesel/diesel blends in diesel engines has been shown to be not only feasible, but also favorable in terms of lubricity and most-regulated pollutant emissions [4]. Due to the great potential of BDF in the transportation industry [5], some studies have reported on the measurement and characterization of particulate matter and gaseous emissions collected from the exhaust flows in internal combustion engines and gas turbines [6,7]. In recent years, BD research efforts have been focused on the synthesis processes, type of catalyst, and performance of this alternative fuel [8–12]. Numerous studies have been conducted on the thermo [13,14], catalytic pyrolysis [15–17], and heat of combustion, and these properties have also been studied by varying the blending percentages of BDF with petroleum-based fuel [18].

The present experimental study is aimed at understanding the soot formation in controlled coflow laminar diffusion flames formed using two fatty acid methyl esters including: B100CME (100% Canola Methyl Ester), B100SME (100% Soybean Methyl Ester), fuel blending includes B50 and B80. The fuel blending ratio (BD/No. 2 ULSD) is indicated by a ‘‘B’’ with a subsequent number. The number following the ‘‘B’’ represents the percentage of BD in the mixture, for instance B100CME represents a 100% canola methyl ester or neat BD. The effect of soot formation is also studied in these oxygenated fuels by increasing the oxygen content in the oxidizer stream from air to 35%, 50% and 80%. The study is conducted using a nonintrusive laser extinction technique. In the present study canola and soybean biodiesels were used mainly due to their large scale availability, and therefore the impact they can have as alternatives to petroleum-based fuels. Canola and soybean oils have lower levels of saturated fats compared to other vegetable oils resulting in a BD with very low Cloud Point (CP) which allows the methyl esters to perform better than other BDF at lower temperatures [19]. The CP for CME and SME is 0 °C and 1 °C, respectively [19]. The CP is defined as the temperature that allows small, solid crystals to form in a fuel as it is cooled. Oil generated from canola feedstocks is considered an excellent lubricant in engines operating under extreme heat and steam conditions [20,21]. The oil adheres to metal surfaces better than any other oils generated from feedstocks. The production rate of a certain type of a BDF is largely a factor of the ability to produce its feedstock at a large scale. Canada is the largest producer of canola seed producing 7 million tons each year [20]. In 2008 it was reported that Canada produced 1.6 million tons annually of canola oil [22,23]. The United States and Brazil are the major producers of soybeans in the world. The total production of BD in the U.S. in June 2014 was 100 million gallons [24]. A total of 822 million pounds of feedstocks were used to produce BD in the U.S. alone in the month of June 2014 with soybean oil ranking as the largest biodiesel feedstock with 467 million pounds [24].

Studies of engines running with diesel fuel and soybean oil BD comparing the performance and emissions at certain engine running conditions have been performed by Canakci et al. [25]. In that study it was shown that CO emissions were 18% lower for neat soybean BD compared to neat petroleum-based diesel. In the same study it was shown that the concentration of NOx emissions is reported to increase in the flue gas by 12% when running with a soybean BD (due to the content of oxygen in the BD) compared to the neat petroleum-based diesel. The particulate matter (PM) from neat soy and canola BD is also shown to be significantly reduced in size during a combustion process [26]. These reductions are principally due to the oxidation rate of BD which can be as much as six times that of diesel. Most recently the study of soot nanostructure from a light-duty diesel engine running with various blending ratios of fuel (ULSD/SME) was reported by Vander Wal et al. [27]. Through high resolution transmission electron microscopy that work aimed to study the physical presence of soot nanostructure as fullerenic shells and/or graphitic lamellae correlated to BD blend ratio.

Studies using diesel engines can provide useful information such as structural characteristics of the particulate matter and gaseous species emitted from diesel engines collected from the exhaust subsequent to the combustion process. However, the products in the exhaust normally undergo a dilution process of clean dry air. Dilution ratio and residence time in the dilution tunnel can lead to products in the exhaust with particle size distribution and chemical compositions that are different. However, fundamental studies directly inside a controllable laminar diffusion flame can suppress some of the physical variables that are encountered in such complex combustors, allowing for a better understanding of the fuel and its characteristic combustion properties. Until recently only very few fundamental studies on the thermal and pollutant emissions have been conducted on BD formed flames [28–32] and on droplet BD combustion [33]. The study of soot formation and other pollutant emissions resulting from BD flames is a nearly unexplored area.

During the last decade new and improved oxygen generation technologies are making the application of oxygen-enhanced combustion (OEC) and or oxy/fuel combustion more affordable and attractive [34]. It is established in the literature that OEC can increase performance in a combustion process. In a typical combustion process (using air as the oxidant) the presence of soot increases the radiant heat transfer efficiency properties which can be significantly further improved by OEC [34]. Over the last decade, OEC and oxy-fuel combustion have been successfully incorporated into a variety of industrial processes, including glass furnaces, boilers, and incinerators [34]. It is known that burning hydrocarbons (liquid fuels/natural gas) with oxygen-enriched air significantly improves the thermal efficiency of the process by increasing the temperature of the flame, flame stability, in addition to a massive reduction in the flue gas volume [34]. Another advantage of OEC addresses the continual increase in the emphasis on the environment. A combustion process with a higher percentage of oxygen can significantly reduce the amount of NOx formed. Given the feasibility of oxygen for increasing (effect on soot and temperature in flame) radiant heat transfer and hence the performance of a combustion process, it is imperative to study and understand the soot particle formation in oxygen and oxygen-enriched air flames formed using these new emerging and alternative form of energy (biodiesel fuel).

2. Experimental setup and procedures

Fig. 1 contains the overall experimental setup used in this study including the coflow burner, liquid fuel injection and pre-