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Optical study on the combustion characteristics and soot emissions of diesel–soybean biodiesel–butanol blends in a constant volume chamber

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ABSTRACT

To investigate the effects of ambient temperature on the combustion characteristics, and soot formation and oxidation, a detailed comparative study between two different volumetric diesel–soybean biodiesel–butanol blended fuels was carried out in an optical constant volume combustion chamber. The volumetric ratios were the 80% diesel/15% soybean biodiesel/5% butanol denoted as S15B5 and 80% diesel/10% soybean biodiesel/10% butanol denoted as S10B10 and were tested in this study with different ambient temperatures (from 800 K to 1200 K) at the start of injection. Experimental results indicated that the ignition delays of the two blended fuels were almost identical, and S15B5 fuel presented higher maximum cumulative heat release, heat release rate and combustion pressure compared to those of S10B10 fuel. With the increase of ambient temperature, the flame propagated downstream of the spray jet and became brighter. The soot distribution was also increased at the downstream of the spray jet with a higher ambient temperature for both blended fuels, and S10B10 had a lower value of normalized time-integrated soot mass (NTISM). Therefore, S10B10 had more advantages to reduce the soot emission compared to S15B5 fuel. Also, increasing the ambient temperature from 800 K to 1200 K led to a rapid decrease in the value of NTISM for both blended fuels.

1. Introduction

Soot emissions from diesel engines remain a serious environmental concern. To meet the increasingly stringent regulations, a number of soot reduction strategies and techniques have been under development. Among these soot reduction strategies, blending biofuels with diesel is seen as a very effective route. Among biofuels, biodiesel is the primary addition or alternative to diesel fuel for compression ignition engines because of its comparable properties to diesel fuel; additionally, it can be blended with diesel in any proportion. Studies with various biodiesel–diesel blends have demonstrated that the blend engines could reduce emissions of carbon monoxide (CO), total hydrocarbons (THCs), and particulate matter (PM), but slightly increase nitrogen oxides (NOx) and brake specific fuel consumption because of the reduction in the lower heating value (LHV) of biodiesel, while the power output for biodiesel was almost the same as that for diesel fuel [1–7].

Biodiesel has higher cloud point and pour point than those of diesel fuel, which means that the cold flow behavior of the biodiesel–diesel blends is poor. In addition, the viscosity of biodiesel is higher, which will affect the spray characteristics and subsequent combustion processes. Some studies have indicated that the low-temperature flow properties of biodiesel could be improved by blending butanol with various volumetric ratios [8,9]. Further, blending butanol into diesel has been reported to achieve improved combustion with a reduction in soot, but higher NOx and CO emissions due to wider combustion high-temperature region and lower gas temperature in the late expansion process [10–12]. Liu et al. [13] studied the effects of oxygenated fuels on the combustion and emissions in a diesel engine. Results indicated that the oxygen in n-butanol was the main factor for soot reduction in comparison with the diesel fuel. The secondary factor for soot

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reduction was the improvement in fuel mixing process due to the longer ignition delay caused by lower cetane number of n-butanol. Zheng et al. [14] investigated the effects of butanol on conventional and low temperature combustion in a single-cylinder diesel engine. Results showed that butanol–diesel blends have the retarded combustion phasing and higher premixed heat release compared with diesel fuel. Valentino et al. [15] carried out an experimental investigation in a modern diesel engine running blends of diesel and n-butanol. The main results showed that the smoke and NOx emissions were reduced for blends due to the longer ignition delay and a better mixing control before combustion. The joint effect of higher resistance to autoignition and higher volatility of n-butanol blends improved emissions compared to diesel fuel with a low penalty on fuel consumption. Merola et al. [16] studied the butanol effects on combustion process through conventional methods and optical diagnostics. The results indicated that smokeless conditions were achieved with a slight increase in NOx emissions and a minor penalty for the specific fuel consumption.

Other studies have indicated soot reduction with the addition of ethanol or butanol in triple fuel blends, such as ethanol–biodiesel–diesel and butanol–biodiesel–diesel blends [17–19]. Yoshimoto et al. [20] examined the influence of 1-butanol addition on the engine performance, combustion characteristics, and exhaust emissions of a small single cylinder direct injection diesel engine using palm oil methyl ester/gas oil blends as the base fuel. The results showed that the brake thermal efficiency of the base fuels changed little when 1-butanol was added up to 40 mass%. At the rated output condition the smoke emissions decreased considerably with increasing 1-butanol addition ratios. In comparison to ethanol, butanol is a more promising alcohol for use in diesel engines [21,22]. Westbrook et al. [23] and Kohse-Hoeinghaus et al. [24] concluded that esters were less effective than alcohols or ethers given the same mass fraction of oxygen. They attributed this difference to both O atoms remaining bound to the single C atom, leading to a considerable fraction of carbon dioxide (CO_2) formation from the ester. Liu et al. [25] studied the combustion characteristics and soot distributions of neat butanol and neat soybean biodiesel in an optical constant-volume combustion chamber at different ambient temperature and indicated that butanol had a higher normalized peak pressure and a lower value of NTISM under all conditions.

On the basis of surveying the literatures, it can be found that ethanol, butanol, and biodiesel are all potential biofuel replacements for diesel engines. It is difficult to isolate the effects of basic parameters (e.g., injection pressure, in-cylinder gas temperature or pressure) on the soot process based on engine experiment. Therefore, in this paper, the diesel–biodiesel–butanol blended fuels are tested in an optical constant volume combustion chamber to create well-characterized conditions with various ambient temperatures, ranging from 800 K to 1200 K. The study is significant to reveal the effects of different butanol additives in biodiesel–diesel blends on the combustion characteristics, soot formation and oxidation by using the forward illumination light extinction (FILE) method.

2. Experimental apparatus and procedure

The experiments were conducted in a constant volume combustion chamber, which is shown in Fig. 1. This chamber was able to simulate the thermodynamic condition inside a diesel engine. The operating conditions, such as the ambient pressure, temperature, density, injection duration, and injection pressure, etc., were adjusted accordingly, so that a wide range of diesel in-cylinder thermodynamic conditions could be simulated. The combustion chamber was optimized for optical access and was fitted with a Caterpillar direct injection hydraulic-actuated electronic-controlled unit fuel injector. The injector had six orifices with separate chambers for hydraulic oil and fuel. It was mounted in the head and pointed upwards with the spray making a 22° ascension angle measured from the head surface. The fuel came out of the nozzle tip at around 1.2 ms from the moment the injector was triggered. The combustion chamber had a bore of 110 mm and a height of 65 mm. A spark plug and a pressure sensor were installed in the chamber wall. Optical access was provided by Dynasil 1100 fused silica located on the top side of the chamber, as shown in Fig. 1. The optical windows had high ultraviolet (UV) transmittance down to 190 nm. The chamber was heated with cartridge electric heaters to simulate an engine wall temperature of 380 K and to prevent water condensation on the windows. The end window on the top of the chamber was used for this study and one of the six spray jets was examined.

The experimental procedure used to simulate diesel fuel injection and combustion processes in a constant-volume combustion chamber was developed previously [26]. The chamber was first filled with different gases at a specified density, and then the mixture was ignited using the spark plug, producing a hot and high-pressure environment in the chamber similar to the real engine combustion chamber. After the premixed gas combustion occurred, the mixture within the chamber slowly cooled down due to the heat loss through the chamber wall and windows, and as a result the chamber pressure decreased. When the desired pressure was reached, the injector was triggered and the fuel injection, autoignition, and combustion processes ensued. The density, temperature, and composition of the ambient gas inside the chamber at the time of injection could be varied to simulate different working conditions in a diesel engine. The chamber used in this study allowed an ambient density up to 30 kg/m^3, which was about 25 times the room air density. Acetylene was chosen as the premixed burnable gas and different amounts of oxygen/nitrogen determine how much oxygen was left in the chamber after premixed gas combustion. For example, to simulate the oxygen concentration of 21 per cent and the density of 15 kg/m^3 inside the chamber for spray combustion, 4 per

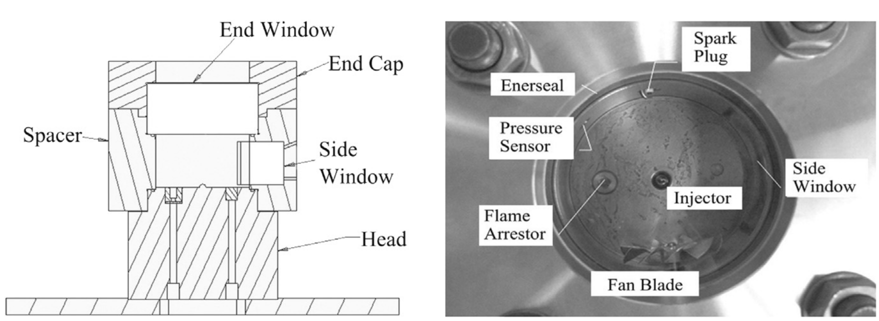

Fig. 1. Schematic of the constant volume chamber.

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