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Full Length Article

Spray combustion of biomass-based renewable diesel fuel using multiple injection strategy in a constant volume combustion chamber

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HIGHLIGHTS

- Spray combustion of biomass to liquid fuel was tested in a constant volume combustion chamber.
- Two injection strategy was investigated using multiband flame emission and two-color pyrometry.
- Lower soot is generated for biomass to liquid fuel compared to diesel.
- Soot temperature is lower for the two-injection strategy for both fuels.

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ABSTRACT

Effect of a two-injection strategy associated with a pilot injection on the spray combustion process was investigated under conventional diesel combustion conditions (1000 K and 21% O_2 concentration) for a biomass-based renewable diesel fuel, i.e., biomass to liquid (BTL), and a regular No. 2 diesel in a constant volume combustion chamber using multiband flame measurement and two-color pyrometry. The spray combustion flame structure was visualized by using multiband flame measurement to show features of soot formation, high temperature and low temperature reactions, which can be characterized by the narrow-band emissions of radicals or intermediate species such as OH, HCHO, and CH. The objective of this study was to identify the details of multiple injection combustion, including a pilot and a main injection, and to provide further insights on how the two injections interact. For comparison, three injection strategies were considered for both fuels including a two-injection strategy (Case TI), single injection strategy A (Case SA), and single injection strategy B (Case SB). Multiband flame results show a strong interaction, indicated by OH^* emissions between the pilot injection and the main injection for Case TI while very weak connection is found for the narrow-band emissions acquired through filters with centerlines of 430 nm and 470 nm. A faster flame development is found for the main injection of Case TI compared to Cases SA and SB, which could be due to the high temperature environment and large air entrainment from the pilot injection. A lower soot level is observed for the BTL flame compared to the diesel flame for all three injection types. Case TI has a lower soot level compared to Cases SA and SB for the BTL fuel, while the diesel fuel maintains a similar soot level among all three injection strategies. Soot temperature of Case TI is lower for both fuels, especially for diesel. Based on these results, it is expected that the two-injection strategy could be effective in reducing soot and NO_x (due to lower combustion temperature) simultaneously compared to either of the single injection strategies.

1. Introduction

In order to further reduce soot and NO_x and meet the more stringent emission standards, multiple injection strategies received considerable attention in advanced diesel combustion [1–13]. It has been shown that multiple injection strategies are promising to reduce soot and NO_x significantly without a substantial penalty in fuel economy. Pilot and post injections are the two typical injection types in multiple injection strategies. A pilot injection is

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Abbreviations: ASOIT, after start of injection timing; BTL, biomass to liquid; CO, carbon monoxide; FILE, forward illumination light extinction; FWHM, full width at half maximum; GC/MS, gas chromatography mass spectrometry; GDI, gasoline direct injection; GTL, gas to liquid; HC, hydrocarbon; HCCI, homogeneous charge compression ignition; LII, laser-induced incandescence; NO_x, oxides of nitrogen; PLIF, planar laser-induced fluorescence; SA, single injection A; SB, single injection B; TI, two-injection.

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generally a short injection with a small quantity of fuel and occurs at an injection timing much earlier than the main injection. This small fuel quantity can be used to control the main injection combustion and reduce engine noise. The main injection occurs after the pilot injection with a large portion of fuel and heat release. Additionally, a pre-injection is similar to the pilot injection in terms of fuel quantity, which is sometimes included in the multiple injection strategy in modern diesel engines, occurring very close to the main injection. Lower emissions and better performance can be realized successfully in different engines with multiple injections [1,2,4]. A pilot injection followed by a main injection combined with a high injection pressure could reduce NO_x by 35% and smoke by 60–80% without increasing the fuel consumption compared to a single main injection [11]. The effect of a pilot injection on combustion noise and emissions was studied by Durnholz et al. and the noise level and NO_x emissions were reduced while maintaining similar soot level [12]. However, a penalty in increased fuel consumption was reported when a multiple injection strategy was executed with varied distribution and dwell time between the pilot and the main injections, even though a simultaneous reduction of soot and NO_x was obtained [4,13].

Recently, it was reported that a pilot injection can also be used to reduce net soot production with varied dwell times [14]. A spatially separated pilot injection was proposed to reduce soot and NO_x without any penalty to efficiency [10,15]. Heat release split, optimized fuel distribution, and a cooling effect of the vaporizing fuel for the multiple injection strategies were considered to improve the noise, emission and fuel economy [16], especially for low temperature combustion [17]. A split injection strategy was studied in a heavy-duty diesel engine using a two-color diagnostic method [18]. Results showed that advancing the pilot injection timing led to a lower peak in-cylinder pressure, a shorter ignition delay of the main injection, and a reduction of soot and NO_x emissions while HC and CO emissions were increased. On the other hand, a pilot injection was reported as a negative factor for gas to liquid (GTL) fuel when it was used to reduce combustion noise while producing a larger amount of soot [19]. The results also showed that there was no effect of a split injection on the timing of pressure peaks and no combustion phase changing occurred as the pilot injection timing was changed.

Regarding to the effect of fuel properties on engine performance and emissions, pure biofuel such as biodiesel (fatty acid methyl ester) was demonstrated for soot reduction either in real engines [20–23] or in constant volume chambers [24–28]. On the other hand, blends of biofuel with traditional fossil fuel was shown to be a promising strategy for the reduction of soot, HC, and CO emissions and the improvement of engine performance [29–32]. The soot reduction mechanism for biodiesel was proposed by Song et al. [33]. It was suggested that the oxidative reactivity of soot is much higher for biodiesel compared to diesel due to greater surface oxygen functionality, which means the acceleration of soot oxidation involved with oxygen groups located at the soot surface. High NO_x emissions from biodiesel combustion were noticed in a few studies [34–36]. It was reported that changing fuel molecular structure was an effective way to improve soot and NO_x emissions [37]. It was pointed out that lower NO_x emissions could be achieved by using biodiesel with shorter fatty acid chains and the formation of NO_x was controlled by the lower flame temperature [38]. On the other hand, local stoichiometric conditions for biodiesel were expected to produce higher thermal NO_x emissions [39]. Different alternative fuels were used in combination with multiple injection strategies to achieve further emissions reduction and performance improvement [6,8,19].

During a typical diesel spray combustion event, OH, CH, HCHO, and C_2 radicals or intermediate species are often generated and can be used for identifying the active reaction regions [40,41]. CH^* and $HCHO^*$ (formaldehyde) radiation emissions were considered as the major contributors to the chemiluminescence signal observed during the low temperature reactions prior to the onset of soot formation [42]. OH^* emission is often considered as the marker of high temperature reactions. A large amount of OH^* emission is observed normally in the downstream region of a spray flame [43]. Even though $HCHO^*$ emission extends to cover 310 nm and 430 nm wavelengths, the intensity of OH^* and CH^* are much higher than that of $HCHO^*$ at the wavelengths of 310 nm and 430 nm respectively [40], therefore, the interference of $HCHO^*$ to OH^* and CH^* can be neglected. Flame-induced reaction front propagation was investigated by using $HCHO^*$ and OH^* chemiluminescence in a gasoline direct injection (GDI) optical engine [44]. Mancaruso et al. [45] investigated the auto-ignition and combustion in the homogeneous charge compression ignition (HCCI) mode in a diesel engine based on the OH^* measurement. Simultaneous OH^* and $HCHO^*$ measurements were conducted by Collin et al. [46] to characterize different combustion stages. $HCHO^*$ distribution was measured at different times by using a simultaneous single-short planar laser-induced fluorescence (PLIF) imaging technique in order to visualize the ignition process for multiple injections of n-Dodecane [47]. The spatial and temporal evolution of various radical species can provide deeper insight and help further understand the multiple injection combustion.

The distribution and concentration of soot generated during spray combustion can be measured using several methods. Laser-induced incandescence (LII) is commonly used in measuring soot volume fraction in both constant volume combustion chambers and optical engines [48–50]. This technique can provide a two-dimensional quantitative measurement of volume fraction, but it relies heavily on calibration, LII models for absorption, conduction, oxidation, sublimation, and annealing, laser fluency and the refractive index function. Two-color pyrometry is widely employed to measure soot concentration (KL factor) and temperature in spray combustion [51–53]. It is relatively easy to implement to measure the temporal and spatial soot evolution even under high soot load conditions. However, it is a line of sight measurement and depends upon calibration, flame surface condition, and wavelength selection. It should be pointed out that there is no strong correlation between two-color-method-resolved KL factor and soot volume fraction/concentration obtained from other soot measurements due to the line-of-sight nature of the two color method. Light extinction is also often used in soot measurement [54,55]. A forward illumination light extinction technique (FILE) was used in soot measurement by Xu and Lee [56]. It should be noted that each technique has its own limitations due to the uncertainty of the refractive index and the uncertainty in the shape or agglomeration characteristics of the soot plume. Photochemical effects also have an impact on LII over a wide range of detection wavelength [57]. Although measurements using the two-color method can be affected by soot concentration gradients along the line of sight [58], it can be used to study the downstream soot distribution where most planar laser or extinction techniques are difficult to apply due to high soot opacity.

From this brief review, it is seen that the multiple injections strategy using a pilot injection can be an effective approach to reduce the soot and NO_x emissions as well as combustion noise in diesel engines. However, it also brings the possible increase of HC, CO, soot and fuel consumption if the multiple injection strategy is not well optimized. The details of spray combustion associated with the pilot injection and the interaction between the pilot injection and the main injection are still not well understood. In order to reveal the details of the interaction between the pilot injection and the main injection, a two-injection strategy, meaning a pilot injection followed by a main injection, was studied for BTL and diesel fuels under a conventional diesel combustion condition.