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Experimental and analytical study on capture spray liquid penetration and combustion characteristics simultaneously with Hydrogenated Catalytic Biodiesel/Diesel blended fuel

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HIGHLIGHTS

- Simultaneous capture of the ignition delay, liquid length and lift-off length.
- The liquid length under reaction was studied by laser (532 nm) Mie-scattering.
- Combustion of HCB was studied by OH* fluorescence and high-temperature luminescence.
- The effect of CN on lift-off length was interpreted by a refined theory.

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ABSTRACT

Hydrogenated Catalytic Biodiesel (HCB), with excellent volatility and cetane number while without contain oxygen and aromatic hydrocarbons, have great potential to improve engine performance and emission characteristics. In this study, the effect of HCB/Diesel blended fuels properties (by mass fraction of biodiesel in diesel) on spray combustion characteristics was investigated at inert and reacting conditions in a constant volume combustion chamber. Laser (532 nm) Mie-scattering, OH* chemiluminescence and high-temperature luminosity were used to capture the spray liquid length, flame lift-off length and ignition delay simultaneously with the help of two intensifier charge coupled device cameras and a high speed Complementary Metal Oxide Semiconductor camera. Encouraging results were obtained at different ambient conditions (temperatures, densities, oxygen concentration) and injection pressures. The results showed that fuels with high cetane number generate shorter ignition delay, and faster auto-ignition results in a shorter flame lift-off length. A new theory was used to interpret the effect of cetane number on lift-off length. Under reacting conditions, the combustion heat release shorten spray liquid length apparently as compared with the results under inert conditions. The liquid length was slightly affected by the injection pressure and oxygen concentrations under both reacting and inert conditions, while the flame lift-off length is significantly influenced by ambient parameters and injection pressure.

1. Introduction

Diesel engines are widely used in vehicles, power generation and agriculture due to their high thermal efficiency, good power performance, high fuel economy and reliability [1,2]. However, because of the global energy crisis and environment issues, the application of renewable clean alternative fuels has been a necessary pathway to deal with increasingly stringent fuel economy and emission regulations

Abbreviations: ASOI, after the start of injection; CMOS, complementary metal oxide semiconductor; CNG, compressed natural gas; CN, cetane number; CWL, central wavelength; CVCC, constant volume combustion chamber; DI, direct injection; DME, dimethyl ether; ECN, engine combustion network; EGR, exhaust gas recirculation; FAME, fatty acid methyl ester; GC-MS, gas chromatography-mass spectrometer; HCB, hydrogenated catalytic biodiesel; HC, hydrocarbon emissions; ICCD, intensifier charge coupled device; ID, ignition delay; LL, spray liquid length; LOL, flame lift-off length; NO_X, nitrogen oxide; PID, proportion integration differentiation; T_i, ignition temperature; T_r, reactant temperature; T_p, high temperature combustion product; UV, ultra-violet lens

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[3–5]. Among alternative renewable fuels, such as Compressed Natural Gas(CNG), Hydrogen, Bio-alcohol and Ethanol, Dimethyl Ether(DME), biodiesel has attracted more attention because it can be directly used in diesel engines with little or no modifications and it is also easily produced from biological feedstock [6–8]. In addition, biodiesel is free of aromatic hydrocarbon, and therefore its performance with regards to combustion and the potential of reducing vehicular emissions are better [9,10].

Hydrogenated catalytic biodiesel(HCB) from waste cooking oil is normally regarded as a "second-generation" biodiesel, attracting more attention in recent years. It is produced by catalytic cracking and hydrogenation process which are different from traditional technology [11]. Firstly, because the molecular structure of HCB is similar with that of diesel, it can be blended with diesel in any ratios homogenously; secondly, without oxygen and nitrogen, it could reduce sulfide and NO_x emissions, and alleviate the effect of fatty acid methyl ester (FAME) biodiesel on engines [12,13]. Di [14] and Rakopoulos [15] have studied the emission characteristics in a direct injection (DI) diesel engine with biodiesel/diesel blended fuel. Their results show that biodiesels have emission reduction potential although they also contribute in increasing thermal efficiency and NO_x emissions due to their oxygen component. HCB is predicted to have better emission performance because it free of oxygen and aromatic compounds. However, its application on engines still needs experimental verification, since currently the optical experimental research performed to investigate the combustion characteristics of HCB are less.

The axial penetration of liquid phase in spray, called liquid length (LL), is an important parameter which has a great influence on combustion and emission characteristics. Optimum LL contributes to a good fuel-air mixture in the combustion chamber, while too long may lead to spray wet walls, which may largely increase soot and reduce the engine efficiency [16–19]. Formerly, the LL was studied by visualization methods (shadow photography, Mie-scattering, etc.) at room temperature, which does not reflect the actual operating condition [20,21]. Siebers [18,19] investigated the LL in evaporating spray with Mie-scattering method under inert conditions. After numerous data analysis, a scaling law of the LL was developed by applying jet theory to a simplified model of spray. The scaling law takes into accounts the geometry of the injector, the fuel properties and the thermodynamic conditions within cylinder, and it provides significant insight into the fuel vaporization process [19]. With shadow photography, Browne [22] studied the LL of spray by comparing different fuel under various conditions. The results show that the LL is equal to spray vapor-phase penetration at the beginning of the fuel injection. Afterwards the LL reaches a maximum value and remains constant while the injection progresses. Lequien [16] measured the LL of diesel sprays under reacting condition and found that fresh air close to the injector nozzle tip are the main part of air entrainment into the jet and therefore controls the LL. Other literatures [23–25] also show that fuel properties (composition, density, boiling point, etc.) have strong impact on LL. Another major parameter is the flame lift-off length (LOL), which is defined as the distance from the nozzle to the farthest upstream location of the high temperature combustion. Optimal LOL can enhance sufficient air entrainment of the spray, enhance uniform fuel-air mixtures. This results in a good engine performance with fewer soot and lower HC emissions [26–28]. Chartier [29] found the influence of inlet temperature and the interval between inlet fuel on LOL with a multiple orifice nozzle injector. Moreover, the ignition delay (ID) is also a significant parameter that cannot be ignored. Pickeet [30] has found that LOL has significant correlation with ID, and the stabilization of LOL is determined by the auto-ignition. Payri [31] investigated LOL and ID with the injector from the Engine Combustion Network (ECN) via chemiluminescence and schlieren techniques, and results show that the effects of oxygen concentration and ambient density are caught differently.

Optically accessible constant volume chamber is a powerful tool to study the spray combustion characteristics because it can be used to replicate the relevant ambient engine operating conditions [18,31–33]. However, few studies have been used to measure the LL, ID and LOL simultaneously. In addition, it is quite difficult under reacting condition to use ordinary optical to measure LL, ID and LOL, because the light scattering from liquid phase is challenging to exactly distinguish due to strong soot radiation illumination [34–36]. Therefore, this paper proposes to combine laser (532 nm) Mie-scattering, OH* chemiluminescence and high-temperature luminosity [32,37,38] to study spray, ignition and combustion characteristics of this new second-generation biodiesel (HCB) by measuring the LL, LOL and ID simultaneously at different operating conditions. The paper is organized in the following ways: In Section 2, the physical and chemical properties of HCB are described in details with the facilities and the methodologies. Also several key parameters are determined during the experiment, determined at various operating conditions are described. That is followed by the results and discussion in Section 3 and conclusions in Section 4.

2. Experiment setup and methodology

2.1. Fuel

HCB is generated from waste cooking oil which can be directly obtained as long chain saturated aliphatic hydrocarbons under the action of the catalyst [39]. Fig. 1 shows the constituents by Gas Chromatography-Mass Spectrometer (GC-MS). The main components are heptadecane, hexadecane and pentadecane. Detailed of the compared properties of HCB, $0^{\#}$ diesel (purchase from SinopecChina) and FAME are shown in Table 1. As mentioned [39], the CN (up to 103.3) and freezing point (up to 14 °C) of HCB are too high to be applied directly into engines, and the process of improvement (reducing the CN and freezing point) is more complex and expensive due to the usage of Pt as a catalyst. Therefore, the pure diesel was used as the baseline fuel and five different blends fuels were employed in this experiment. Previous studies [39,40] showed that the test fuels have greater potential for engine applications and soot reduction.

The quantity of the blended fuel is determined by HCB. That is HB0, HB10, HB20, HB30, HB40 and HB50, the corresponding to mass fraction of HCB is 0% (pure diesel), 10%, 20%, 30%, 40% and 50% respectively. Table 2 shows the properties of the blended fuels. The CN of each blended fuel was calculated from formula in reference [15,41]. The kinetic viscosity and density were measured by NG-55 viscometer and densitometer.

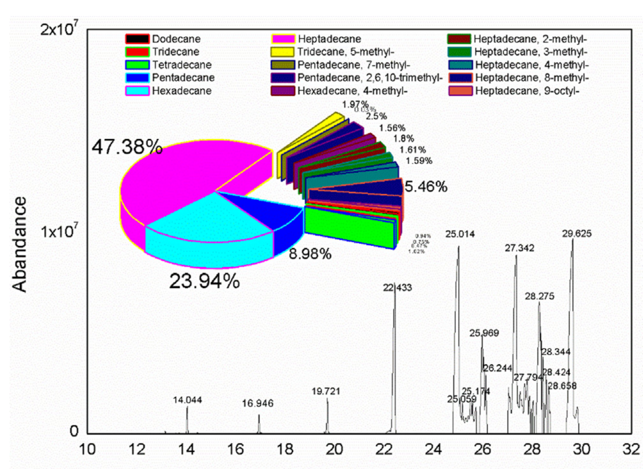

Fig. 1. Constituents by GC-MS.