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Research Paper

Experimental study of the ignition delay of diesel/biodiesel blends using a shock tube

*Vu Nguyen Hoang, Luong Dinh Thi**

Le Quy Don Technical University, Hanoi, Vietnam

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Ignition delays of a pure biodiesel, which is produced from palm oil, as well as its blends with petroleum diesel were experimentally quantified using a preheated shock tube. The emission of OH^* radical signals, which was observed by a photomultiplier via a monochromator, was used to identify the time for onset of ignition. Experiments were performed behind the reflected shock waves at a pressure of 0.12 MPa, equivalence ratios of 0.5, 1.0 and 1.5, and a range of temperatures from 1174 to 1685 K. Fuel blends B0, B20, B40, B60, B80 and B100 (corresponding to 0, 20, 40, 60, 80 and 100 vol% of biodiesel with petroleum diesel, respectively) were tested. The results show that ignition delay variations of blends versus temperature were similar to those of pure diesel fuel. It was consistently found that for all fuel blends, ignition delay increases with an increase in equivalence ratio. An equivalence ratio exponent of 0.73 in Arrhenius correlation was observed. At a constant equivalence ratio, the effect of biodiesel fraction on chemical ignition delay of the fuel blends was not significant. The overall activation energy of diesel/biodiesel mixtures in this study is 161,937.5 J mol^{-1}.

1. Introduction

With more world-wide energy consumption and increased shortages of fossil-based fuels, much research has focused on energy saving and reducing environmental pollution. Biodiesel is a clean burning alternative fuel produced from renewable resources such as vegetable oils and fats (Shao, He, Sun, & Jiang, 2009). It is becoming one of the most promising alternative fuels for global energy demands (Bo & Rosnah, 2014). Blends of biodiesel with petroleum diesel have been tested in diesel engines (Hifjur & Sweeti, 2014) and showed reductions in tailpipe emissions such as soot, carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC) and NOx without significant changes having to be made to the engine design.

Biodiesel is long-chain mono alkyl ester mixture which is converted from plant oils, recycled cooking greases and oils, or animal fats. It usually consists of fatty acid methyl esters (FAME) produced through a process called transesterification.

Ignition delay is the one of important parameters in combustion process of fuels, it directly impacts on the heat release rate and the timing of the onset of ignition in the thermodynamic cycle of an engine. It also indirectly affects engine performance, noise generation and pollutant formation. Measurements used shock tube facilities to obtain the chemical ignition delays of diesel and biodiesel are reviewed as follows.

* *Corresponding author*. Tel.: +84 974922757.
E-mail address: thidongluc33@yahoo.com (L.D. Thi).
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Nomenclature

Abbreviation

B0	Pure diesel
B20	Blend of 80% diesel with 20% biodiesel
B40	Blend of 60% diesel with 40% biodiesel
B60	Blend of 40% diesel with 60% biodiesel
B80	Blend of 20% diesel with 80% biodiesel
B100	Pure biodiesel
CEE	Cotton ethyl ester
CH^*	Hydrocarbon radical
C/H/O	Fraction of carbon, hydrogen and oxygen in fuel
FAME	Fatty acid methyl esters
HC	Unburned hydrocarbons
H/C	Ratio of hydrogen and carbon
HPLC	High performance liquid chromatography
MLR	Multiple linear regression
OH^*	Hydroxylation radical
PME	Palm methyl ester

Symbols

A	Coefficient determined from multiple linear regression method
E_a	Global activation energy, J mol^{-1}
R	Universal gas constant, J mol^{-1} K^{-1}
p	Pressure, MPa
T	Temperature, K
α	Pressure exponent
β	Temperature exponent
τ	Ignition delay, μs
ϕ	Fuel-air equivalence ratio

Ignition delay of three large normal alkanes (n-decane, n-dodecane and n-hexadecane); methyl decanoate; and several diesel types (DF-2 with a range of cetane indices from 42 to 55) was studied using a shock tube (Haylett, Davidson, & Hanson, 2012). At high temperature, the measured ignition delay of lean mixtures was significantly longer than those of rich mixtures, and their measured ignition delay of rich mixtures was a little bit shorter than their model predictions. Ignition delay of methyl oleate and methyl linoleate (biodiesel surrogates) at very low vapour pressure was measured by Campbell, Davidson, Hanson, and Westbrook (2013) using an aerosol shock tube. It was reported to be similar over the experimental conditions. Differences between experimental and computed results were strongly related to existing errors and uncertainties in the thermochemistry of the large methyl ester species. Ignition delay of DF-2 diesel/21% oxygen/argon mixtures was measured by Haylett, Lappas, Davidson, and Hanson (2009) using an aerosol shock tube. Their measurements provide an accurate database for validation on the kinetic mechanisms of diesel fuel and surrogates. Lancheros et al. (2012) measured ignition delay of surrogate biodiesel fuels in a high-pressure shock tube. Their kinetic mechanism yields improved predictions of profiles measured earlier and it also agreed fairly well with the experimental data over the conditions in this study. Saleh (2011) carried out an experimental study for ignition delay of cotton methyl ester, cotton ethyl ester (CEE) and CEE – diesel blends from neat cottonseed oil using the shock tube, he found that the minimum ignition delay was observed at an equivalence ratio of 1.05 for all the tested fuels.

Although the previous studies for ignition delay of diesel and biodiesel fuel are numerous, the data obtained are not sufficient to fully understand their combustion characteristics due to the diversity of biodiesel and complexity of their detailed kinetic mechanisms. Many kinetic mechanisms for biodiesel have been developed recently (Herbinet, Pitz, & Westbrook, 2008; Herbinet, Pitz, & Westbrook, 2010; Olchanski & Burcat, 2006; Wang et al., 2010), but these mechanisms still need to be validated by experimental data. Therefore, it is necessary to continue with experimental investigations in order to improve our understanding of the auto-ignition characteristics of biodiesel and its blends.

2. Experimental setup

The experiments were conducted behind the reflected shock wave in a preheated stainless-steel shock tube (School of Energy and Power Engineering, Xi'an Jiaotong University, http://epe.xjtu.edu.cn/en/). The shock tube and its equipped facilities were schematically shown in Fig. 1 (Thi, Zhang, Fu, Huang, & Zhang, 2014; Thi, Zhang, & Huang, 2014).

The shock tube has a 2 m long driver section and a 5.3 m long driven section with an internal diameter of 115 mm. Double polycarbonate diaphragms divided the driver and driven sections before each experiment. Thickness of the diaphragms was selected according to magnitude of the reflected pressure. A mixture of helium and nitrogen with different fractions was used as the driver gas to obtain a longer test time. The shock tube was evacuated to a pressure below 0.02 Pa before mixture of He and N_2 was introduced into the driver section and reactant mixture was added into the driven section. Four fast-response sidewall piezoelectric pressure transducers (PCB 113B26 – http://www.pcb.com/Products.aspx?m=113B26) are located at fixed intervals (300 mm) along the end part of driven section. Three time counters (FLUKE PM6690 – http://www.ttid.co.uk/products-resale/fluke/fluke-counters-6690-spec.htm) were used to record time intervals when the incident shock wave passed each transducer and the incident shock velocity was then correspondingly calculated.

The shock wave velocity at the end-wall was calculated by linear extrapolating the shock velocity profile to the end-wall, velocity uncertainty is approximately 0.2%. Typical attenuation rates of the incident shock ranged from 0.3 to 0.6 % m^{-1}. On the end-wall, a 5th pressure transducer (PCB 113B03 – http://www.pcb.com/products.aspx?m=113B03) was installed to measure the pressure behind the reflected shock wave, uncertainty in the pressure measurement was approximately 1%. Additionally, a photomultiplier (Hamamatsu CR131 http://www.hamamatsu.com/eu/en/index.html) and a quartz-glass window together with a 307.8 nm narrow band pass filter were mounted at the same position to capture OH^* emission.

Temperature behind the reflected shock wave was calculated through the measured shock wave velocity by using the