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Ignition delay, combustion and emission characteristics of Diesel engine fueled with rapeseed biodiesel – A literature review

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ABSTRACT

Biodiesel is one of the biodegradable and renewable fuels, which is originated from vegetable oil or animal fats. Rapeseed biodiesel is a kind of biofuel which is gaining acceptance in the market due to many environmental and economic benefits. It can be used alone or in a blend with Diesel fuel, directly in compression ignition engines, without any modifications. This review collects and analyzes published papers concerning the usage of rapeseed biodiesel as an alternative fuel in Diesel engines. It covers engine combustion, performance and emissions characteristics. Research results reveal that rapeseed biodiesel, either pure or blended with Diesel, has lower heat release rate, reduced ignition delay, lower thermal efficiency and higher brake specific fuel consumption. Carbon monoxide (CO) and particulate matter (PM) exhaust emissions are up to 60% lower, while carbon dioxide (CO_2) and nitrogen oxides (NO_x) are higher in comparison to Diesel fuel. This behavior is explained by the shorter ignition delay and advanced fuel injection when using rapeseed oil.

1. Introduction

Increased environmental concerns, depletion of petroleum resources and increasing industrialization and modernization of the world have caused researchers around the world to look for alternative fuels from renewable resources. These fuels should be available, economically viable and environmentally acceptable. Biodiesel is one of a few promising alternative fuels. Biodiesel is composed of fatty acids produced via chemical processes from vegetable oil such as rapeseed oil, soybean, palm oil, etc. or animal fat. Appropriate utilization of renewable straight vegetable oil (SVO) as fuel, replacing fossil fuel, contributes to climate, water and soil protection and enables a reduction of greenhouse gas emissions [1]. Biodiesel has a lower aromatic compound content, with (10–12% oxygen by weight), and is free of Sulphur content. These characteristics contribute to the reduction in carbon dioxide, carbon monoxide, unburned hydrocarbons and soot emissions [2–5]. Since biodiesel has a high flash point and lower volatility it is safe to store and handle. Biodiesel has a higher bulk modulus, higher sound velocity, higher viscosity, and higher cetane number than Diesel fuel. These features of biodiesel lead to an advance in the start of fuel injection (SOI) [6].

The major disadvantage of biodiesel is its viscosity [7,8]. Higher biodiesel viscosity can lead to reduced atomization quality, lower spray cone angle, increased average droplet diameter, and longer tip penetration of the sprayed injected fuel. Numerous studies [9,10] have been conducted on the ignition delay of Diesel engines fueled with biodiesel at different engine operation conditions, such as; engine speed, fuel injection timing, injection pressure, engine load, compression ratio etc. The results of these studies revealed that biodiesel has shorter ignition delay (ID) [11,12]. Literature is replete with the disadvantages of using biodiesel: its longer combustion duration, lower rate of heat release, a lower rate of pressure rise, engine power losses, higher brake specific fuel consumption (BSFC). Furthermore, biodiesel has lower volatility, 12% lower heating value and lower energy density, these being the main explanations reported for these behaviors.

Grau et al. [13] reported that the neat rapeseed oil was considered as a potential alternative fuel for an unmodified Diesel engine because it has high oil content (around 40%). Many studies have been conducted to compare the performance of biodiesel obtained from rapeseed oil with that of petroleum based Diesel fuel. Hence, the main objective of this paper is to analyze by means of literature review the ignition delay, engine performance, combustion characteristics and exhaust gas emissions of Diesel engines fueled with rapeseed oil and its blends with Diesel fuel in different fractions. This special focus is on rapeseed oil as alternative fuel because the global rapeseed production has undergone sustained growth in the last two decades. Rapeseed is

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now the second most produced oilseed behind soybeans oil. The major producers are European Union, Canada, China and India. The European Union produces more than ten million tons (MT) yearly of rapeseed oil, major quantities being produced by Germany, Spain, France and Romania. Romania is planning to reach 1.4 MT in 2017, which represents 27% more than in 2015/16, based on current plant development status and the rapeseed planted area of nearly 500,000 ha. This is higher than other biodiesel raw material such as soybean which did not exceeded 1.3 MT in 2015/2016 [14]. Moreover, rapeseed oil historically was used in limited quantities due to its high levels of erucic acid contain.

2. The effect of rapeseed biodiesel on ignition delay (ID)

Ignition delay (ID) is defined as the period between the start of fuel injection and the start of combustion [15]. The start of fuel injection is usually taken as the time when the injector needle lifts off while the start of combustion is more difficult to define. Abrupt change in the cylinder pressure gradient, light emission detected by a photocell, temperature rise due to combustion, the combustion of a certain mass of fuel and the change of slope in the heat release profile are methods used to identify the combustion start [16]. Ignition delay has a direct impact on the heat release rate and an indirect impact on engine noise and exhaust gas emissions formation. The ignition delay period is divided into a physical and chemical delay, with the two-time scales occurring simultaneously [17,18]. During the physical delay period, the fuel injected into a hot and highly pressurized air, is preceded by atomization, vaporization, and mixing with air. The physical delay period depends on the fuel's properties and composition. While, in the chemical delay period, fuel reaction begins slowly and then accelerates until self-ignition takes place. However, chemical reactions depend on cylinder temperature, cylinder pressure and fuel properties. The chemical delay period decreases as the cylinder temperature increases and, generally, chemical delay is longer than physical delay. According to the definition of ignition delay, the more ignition delay increases, the more fuel will be atomized, evaporated and mixed with air, which leads to an increase of the amount of fuel burned and of the rate of heat released in the premixed combustion stage, and vice versa [19]. However, longer delay periods lead to unacceptable rates of pressure rise, with the result of Diesel knock, because a higher amount of fuel is introduced in the premixed combustion.

Golovitchev and Yang [20] conducted an experimental and numerical study on Volvo D12C, direct injection (DI) Diesel engine fueled rapeseed methyl ester at different blends. Results showed that the ignition delay was shorter for all blends and engine operating conditions, when compared to Diesel fuel. These results are similar to those reported in [21]. The effects of the rapeseed oil and its blends based on energy and exergy analyses on engine performance at various operating conditions carried out by [22]. A four-stroke, 1.5l, single-cylinder, Gardner 1L2 compression ignition engine has been utilization in this study. The results showed that the ignition delay period of rapeseed oil and its blends is significantly shorter than that of Diesel and it decreases when rapeseed percentage (blend) increases. This finding is similar to that found in [19,23]. Rodriguez et al. [24] set up a series of virtual experiments using rapeseed biodiesel and its blends in a six-cylinder, Volvo TD60B turbocharged Diesel engine at different operating conditions. The experiments showed that rapeseed biodiesel produced a shorter ignition delay than that of Diesel fuel. The authors explained this reduction in ignition delay is due to the higher cetane number of the rapeseed biodiesel. This reduction in ignition delay of biodiesel was affirmed in studies [25,26].

Several studies investigating the utilization of rapeseed biodiesel and its blends as fuel in compression ignition engine have been carried out in [22,24,27], and reported that higher bulk modulus, higher sound velocity, higher density and higher cetane number of rapeseed biodiesel are responsible for the early start of fuel injection and shorter ignition

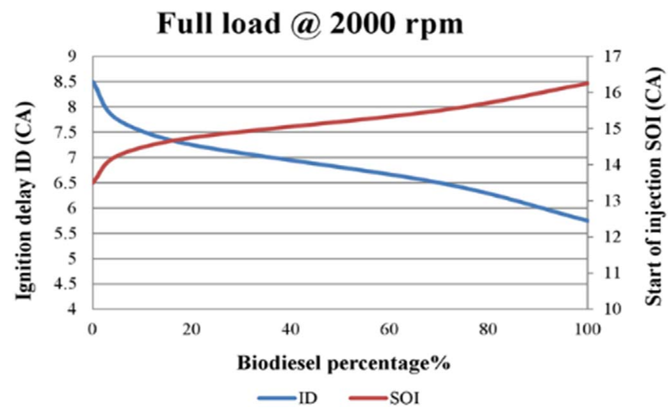

Fig. 1. Variation of the start of injection and ignition delay versus biodiesel percentage. Adapted from Table 4 of [23].

delay. A considerable amount of literature [28–30] has shown that ignition delay period increases when the engine speed and load increases and this may be attributed to the higher combustion temperature and exhaust gas dilution at higher load and speed. Buyukkaya [23] utilized pure rapeseed oil and its blends (5%, 20% and 70% and 100% by volume) in a six-cylinder, four-stroke, DI Diesel engine. The results indicated that ignition delay for all blends was shorter relative to Diesel fuel. That study also concluded that the ignition delay period decreases and the start of injection advances as the biodiesel blend percentages increase as shown in Fig. 1.

Labecki and Ganippa [31] have examined the effect of rapeseed biodiesel Diesel fuel blends on the ignition delay period. The results show that the ignition delay period of rapeseed oil and its blends are shorter than those of Diesel fuel and it decreases with the increase of the percentage of rapeseed oil. Moreover, these authors observed that in general there is a trend of decreasing the ignition delay by increasing the engine load. They explained this behavior by the presence of a high oxygen content in rapeseed biodiesel during combustion process.

Rakopoulos et al. [26] carried out a series of experiments on utilization rapeseed biodiesel in Mercedes-Benz, six-cylinder, turbocharged, heavy-duty, direct injection DI, Diesel engine at engine speeds (1300, 1400 and 1500 rpm), and different engine load. These experiments illustrate that ignition delay period of rapeseed biodiesel was shorter than that produced by Diesel fuel at all operating conditions. The shorter ignition delay period with rapeseed biodiesel was explained by the authors through the fact that biodiesel has a small percentage of diglycerides, which have higher boiling points. However, the chemical reactions during the injection of biodiesel at high temperatures resulted in the breakdown of the high molecular weight esters into small molecular weight, thus enabling combustion of volatile compounds ignited earlier and reduced the delay period. The effect of biodiesel and its blends on ignition delay period relative to Diesel fuel for previews studies in different engines is listed in Table 1.

2.1. Ignition delay correlations of rapeseed biodiesel

Many ignition delay correlations have been proposed for Diesel fuel and the most suitable empirical correlations for Diesel engines based on cylinder pressure and temperature are those proposed by Assanis and Watson [24]. The general relationship for the ignition delay is provided by Arrhenius Eq. (1) as shown in [32]:

$$\tau = Ap^{-n} exp\left(\frac{E_A}{RT}\right)\o^{-k} \tag{1}$$

where: τ- ignition delay, EA- activation energy, Ø- equivalence ratio, R- universal gas constant, T- thermodynamic temperature, p -pressure, while, A, n and k are adjustable constants.

There is a difference in the chemical composition and fuel proper-