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The preparation and shock tube investigation of comparative ignition delays using blends of diesel fuel with bio-diesel of cottonseed oil

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ABSTRACT

This paper describes an experimental effort for the production of cotton methyl ester (CME), cotton ethyl ester (CEE) and CEE–diesel blends from neat cottonseed oil (CSO) for use as a bio-diesel fuel and the investigation of the ignition delay times of these fuels using the shock tube. The transesterification of the neat CSO with methanol or ethanol has been performed to determine the optimum conditions for the preparation. The optimum parameters were cottonseed oil/alcohol molar ratio, 1:6; NaOH amount, 1% by the weight of the oil and reaction time, 75 min. The physical properties of all the tested fuels are measured. 89% of the neat CSO was converted into CME or CEE and the use of different alcohols (methanol or ethanol) presents few differences with regards to the kinetics of reaction but the final yield of esters remains almost unchanged. The ignition delay times were measured using a piezo-electric pressure transducer, charge amplifier, data acquisition card, IBM computer and LabVIEW program. Effects of equivalence ratio, initial charge temperature and initial charge pressure on the ignition delay times are discussed. The results show that the minimum ignition delay time was observed at an equivalence ratio of 1.05 for all the tested fuels. The ignition delay can be reduced considerably together with an increase of the initial charge temperatures and pressures. Also, the ignition delays of the tested fuels are compared with the diesel fuel.

1. Introduction

The idea of using vegetable oil as a diesel engine fuel has been around for a long time and dates back to the beginning of the last century when the diesel engine was invented by Dr. Rudolf Diesel. The current effort is directed at improving air quality as well as increasing domestic energy security. Alternative fuels and the vehicles powered by them are viewed as ways to reduce harmful air pollutants and greenhouse gases. In this context, vegetable oil is an alternative fuel for diesel engines that is receiving great attention world wide. Although it attracts the most attention because it is renewable, it can be used either pure or in blends with diesel fuel in unmodified diesel engines, and it reduces some exhaust pollutants. It is also attractive because it can be produced easily from common feedstocks. Nevertheless, various technical and economic aspects require further improvement of these fuels. Numerous different vegetable oils have been tested as bio-diesel. Bio-diesel can be derived from food-grade vegetable oils, nonfood-grade vegetable oils, animal fats, and waste restaurant greases. Often the vegetable oils investigated for their suitability as bio-diesel are those which occur abundantly in the country of testing. Therefore, soybean oil is of primary interest as bio-diesel source in the United States while many European countries are concerned with rapeseed oil, and countries with tropical climate prefer to utilize coconut oil, hazelnut or palm oil [1–3]. Other vegetable oils, including sunflower, rubber, etc., have also been investigated. Furthermore, other sources of bio-diesel studied include animal fats, salmon oil and/or waste cooking oils [4–7].

Raw or refined vegetable oils have significantly different and widely varying properties that are not acceptable for use in modern diesel engines. The higher viscosity and chemical composition of unprocessed oils and fats have been shown to cause problems in a number of areas [8–10]. The significantly higher viscosity of raw vegetable oils (27–54 mm^2/s) compared to petroleum diesel fuel (2.6 mm^2/s) alters fuel injector spray patterns and spray duration, adds stress on fuel injection systems, and results in incomplete combustion and high dilution of the engine lubricating oil [11]. Transesterification is a way to lower the viscosity of the vegetable oil by breaking up the triglyceride molecule and separating the fatty acid molecules from the glycerin molecule. This makes the properties of the vegetable oils and animal fats closer to those of diesel fuel, solving the problems due to the high viscosity of vegetable oils. The methyl esters of vegetable oils (bio-diesel), which are produced by combining methanol with the vegetable oil, are of particular interest; these fuels tend to burn cleaner, perform comparably to conventional diesel fuel.

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Many studies have been reported by several researchers at the Helwan University involving different types of fuel as a primary source of energy for diesel engines [12–17]. Numerous experimental methods have been developed in order to measure the combustion characteristics fundamental such as the laminar burning velocity and the ignition delay of a combustible mixture for coal-derived fuels or jojoba methyl ester by using constant volume bomb or shock tube method. Also, many studies have been done on these fuels in diesel engine for determining the performance and exhaust emissions. In this work, we are interested in determining the ignition delay of cotton seed oil as a vegetable oil fuel for diesel engines in the shock tube. Although numerous studies have been conducted on cotton oil production as bio-diesel and exhaust emission testing for many years [18–26], the ignition delay of neat CSO, CME or CEE has not been searched in any diesel engine or another test rig yet. However, ignition delay is an important variable that influences the combustion chamber design, rate of pressure rise, peak cylinder pressure, exhaust gas temperature, and exhaust emissions. This was the basic motivation behind the research in this paper.

The main objective of the present work was the shock tube investigation of comparative ignition delay times of neat CSO, CME, CEE, CEE–diesel blends, so an extensive test program is set up in the following steps:

1. Optimum conditions for the transesterification of neat CSO with methanol or ethanol have been determined for production CME or CEE.
2. Analysis of the physical properties for neat CSO, CME, CEE, CEE–diesel blends and diesel fuel was carried out.
3. The ignition delay times have been measured for neat CSO, CME, CEE and CEE–diesel blends over a wide range of operating conditions, equivalence ratio, initial charge temperature and pressure.
4. For comparison, the ignition delays of diesel fuel as a reference fuel have been measured at the different conditions.

2. Bio-diesel production

Transesterification is the process of using an alcohol (e.g., methanol or ethanol) in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide, to chemically break the molecule of the raw renewable oil into methyl or ethyl esters of the renewable oil with glycerol as a by-product. A simplified form of the transesterification reaction is shown below.

$$\text{Oil(Triglycerides)} + \text{Alcohol} + \text{Catalyst} \rightarrow \text{Alkyl esters} + \text{Glycerine}$$

There are several factors that affect the quality of conversion by the transesterification process. The first factors to be concerned with are the free fatty acid and moisture content, because the presence of free fatty acids and water causes soap formation, consumes catalyst and reduces the conversion of oil to ester [11]. Important reaction parameters such as molar ratio of alcohol to oil, type of alcohol, amount of catalyst and reaction time were investigated to determine the best strategy for converting the free fatty acids into usable esters [11].

The molar ratio of alcohol to triglyceride is one of the most important variables affecting the yield of ester. The stoichiometric reaction requires one mol of a triglyceride and three mol of the alcohol. However, the transesterification reaction is an equilibrium reaction, so the ratio will be higher than the stoichiometric ratio to drive the reaction towards the desired products. It was reported that the largest ester yield is obtained for 6/1 methanol/triglyceride molar ratio which is the twice of stoichiometric ratio [11,27,28]. Ethanol rather than methanol can be used to produce ethyl ester of vegetable oils. Production of ethanol from biomass is one way to reduce both the consumption of crude oil and the environmental pollution [11,29]. Therefore, in this study, the molar ratio of methanol to glycerides was used as 6/1 and then the molar ratio of ethanol to glycerides was used as 6/1 to obtain the best fuel properties of bio-diesel.

The transesterifications were enhanced by the use of potassium hydroxide, sodium hydroxide, sodium methoxide, or sodium ethoxide as catalysts. NaOH was preferred as a catalyst due to its high activity [11]. Care should be exercised when adding sodium hydroxide to compensate for a high acid value. The addition of excess sodium hydroxide will cause soap formation which will increase the viscosity of the formation of gels and interfere with the reaction and the separation of glycerol [11]. It has been observed that high catalyst concentrations greater than 1.5% lead to the production of large amounts of soaps [11,28]. In this work, three sets of the reaction mixtures were prepared with 0.5%, 1.0%, and 1.5% by the weight of the oil of NaOH catalyst and allowed to react.

Other variables that affect the process yield are reaction time, temperature, and mixing intensity. It has been observed by [30] that the longer the reaction time, the better the conversion percentage; and the rate of transesterification rises with the increase of reaction temperature. However, the maximum operating temperature cannot exceed the boiling point of the alcohol used in the process. So, in this work the oil and alcohol were heated at 60 °C. Mixing is very important to get the reaction started, but once the two phases are mixed the reaction will continue on its own.

In this study, transesterification process was carried out using different variables that are summarized below:

Cottonseed oil/alcohol molar ratio: 1:6
Type of alcohol: methanol or ethanol
The amount of catalyst: 0.5–1.5% by the weight of the oil of sodium hydroxide.
Temperature of reaction was constant at 60 °C
Time of reaction mixture: 30–120 min

The transesterification experiments were performed in a beaker of 2000 ml volume. The beaker is placed in a thermostatic bath to keep the temperature constant throughout the reaction and the beaker was stirred by eclectic motor. The process can be summarized as follows:

1. The cottonseed oil was filtered to remove solid precipitate in the oil and then was subjected to drying by heating at 100 °C for 15 min to obtain very minimal amounts of water in the oil, as any water in the system will consume some of the catalyst and slow the transesterification reaction [11]. Then waited until the oil returns to room temperature.
2. The solid catalyst (NaOH) was added to 200 ml of alcohol (methanol or ethanol) and was dissolved by vigorous stirring. Then the prepared mixture was poured into 800 ml of the cottonseed oil.
3. The beaker was stirred at various times holding the temperature at 60 °C by a thermostatic bath.
4. The reaction mixtures were allowed to react for 30, 45, 60, 75, 90 and 120 min, respectively. Then, the heater was turned off.
5. The reaction was arrested by adding ice crystals of water [13]. The products were allowed to settle and separate into phases; the bottom layer was water, then the middle layer of glycerol and the upper layer was ester, as they have different densities.
6. The top ester layer was poured into another beaker and was washed from the remaining ester and the residual catalyst with 200 ml of water, three times.