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An experimental study on the combustion, performance and emission characteristics of a diesel engine fuelled with diesel-castor oil biodiesel blends

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A B S T R A C T

An experimental work has been performed to compare the combustion, performance and emission characteristics of a compression ignition engine running with diesel and three different blends of diesel and biodiesel (castor oil methyl ester, COME). The biodiesel has been prepared by alkaline transesterification using NaOH as catalyst. The properties of the fuels, like viscosity, surface tension, heating value, flash point and elemental composition, have been measured following standard test procedures. The variation of viscosity and surface tension of the pure fuels and their blends with temperature are experimentally determined. Experiments have also been performed on a porous sphere to compare the mass burning rate and transition velocity from envelope to wake flame for the pure fuels and their blends. The porous sphere experiment results indicate that diesel has higher evaporation rate than COME while the chemical reactivity of the latter is more than the former. The originality of the work is in using the fundamental information from the porous sphere experiments to explain the combustion characteristics in the engine cylinder. Studies in the engine reveal that combustion starts earlier with the diesel-biodiesel blends and the rate of pressure rise during the rapid combustion phase is also faster with the blended fuels compared to that with diesel. However, not much difference has been noticed in the performance (brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature) and emission (CO, HC and NO) characteristics of the engine using the diesel fuel and diesel-biodiesel fuel blends.

1. Introduction

The increased demand of energy in various sectors in the past few decades has resulted in a massive leap in the consumption of petroleum resources. According to the annual report of British Petroleum (Statistical Review of World Energy 2016), the worldwide fuel oil consumption has increased from 3.93 billion tonnes in 2005 to 4.33 billion tonnes in 2015 [1], representing a 10% increase in 10 years' time. The rising trend in consumption is likely to deplete the entire global reserve of petroleum in the next three decades. Shafiee and Topal [2] predicted the depletion time of various fossil fuels considering continuous compound growth rate of fossil fuel consumption and found that the oil reserves will last for only 35 years. At the same time, the large-scale use of petroleum-based fuels results in the degradation of the environment — due to continuous emission of different pollutants — and challenges sustainability. In summary, the dwindling petroleum resources, harmful effects of air pollution, and increase in global warming potential — which is caused due to the emission of greenhouse gases (GHG) like carbon dioxide — have led researchers and planners to look for feasible and economically viable alternatives of conventional liquid fuels. Among the various potential alternatives, biodiesel looks to be a promising substitute of diesel.

Biodiesel presents a number of advantages over conventional petro-diesel. Biodiesel, being an oxygenated fuel, has a higher percentage of oxygen (in most cases, above 10% w/w) [3,4,5] when compared to petro-diesel, which helps in a more efficient combustion of the fuel. It also has a higher cetane number [6,7,8], much lower aromatic content, almost no sulphur, and produces cleaner exhaust gases [9,10,11]. Owing to its higher flash point, it also serves as a safer and more portable alternative to petro-diesel. Moreover, biodiesel is prepared from renewable resources and is also

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biodegradable [3,12]. Apart from these advantages, biodiesel presents two major economic benefits — it reduces a country's dependence on crude oil imports and generates new employment [13,14].

Biodiesel can be produced from a variety of feedstock such as vegetable oils (edible and non-edible), waste or used cooking oil, and animal fats (such as beef tallow, pork lard). Non-edible oils are preferred for making biodiesel compared to edible oils, in order to avoid any conflict with food supply. There are various non-edible oil-seed species, such as *Jatropha curcas* (Jatropha), *Azadirachta indica* (Neem), *Pongamia pinnata* (Karanja), *Ricinus communis* (Castor) and *Madhuca indica* (Mahua) [15], which have been used to produce biodiesel. Among these, castor is a promising resource for biodiesel production because of the higher oil yield potential of castor seeds compared to the other non-edible oilseeds [16,17]. Castor oil plants, seen as branching perennial shrubs or, occasionally, small soft-wooded trees, are fast-growing in nature. Moreover, castor plants are able to withstand harsh weather conditions, such as droughts, and can also grow on marginal lands which are not favourable for cultivation of food crops [18,19]. The oil is non-edible and widely available in the Asian countries, like India and China. However, due to its extremely high viscosity and high water content, raw castor oil is not suitable for direct use in engines.

Various works in the literature discussed the transesterification process for the production of biodiesel from castor oil [19–23]. Most of them suggested alkaline transesterification with a basic catalyst, like sodium hydroxide, potassium hydroxide, sodium methoxide or potassium methoxide. Berman et al. [19] investigated various properties of pure castor oil methyl ester and its 10% blend with diesel (B10). They found that the kinematic viscosity and distillation temperature of pure COME did not meet the prescribed standard of biodiesel following ASTM D6751, while for the B10 blend all the properties fall within the prescribed range. Azad et al. [24] estimated the present global production of castor oil at 1.8 million tons per year and analysed the prospects and challenges of biodiesel production from this oil. They concluded that, not only can castor oil methyl ester (COME) be a good alternative to diesel; it also has good lubricating properties for engines. The performance and emission characteristics of castor oil biodiesel in compression ignition engines have been studied by Panwar et al. [25], Özcanli et al. [26] and Dasari et al. [27]. Panwar et al. [25] studied the performance of a four stroke, single cylinder diesel engine with three different diesel-biodiesel blends (B05, B10, and B20) and compared the results with that of pure diesel (B0). The engine was operated at a constant speed of 1500 rpm. The performance of the blended fuels was found to be close to that of diesel. Özcanli et al. [26] worked with blends of diesel and castor oil biodiesel over the entire range of biodiesel blends (i.e. from 0% to 100% biodiesel). The performance parameters were determined over a range of engine speeds from 1000 rpm to 2400 rpm. Test results showed an increase in brake specific fuel consumption and a small decrease in brake power with the increase in percentage of castor oil biodiesel in the blend. On the other hand, blending castor oil biodiesel reduced carbon monoxide and carbon dioxide emissions but increased NO_x emission. B25 was recommended as the most suitable alternative for diesel engines. However, the above works did not justify the reported engine performance results with the fundamental combustion characteristics of the fuels in use. Dasari et al. [27] considered three blends of diesel and castor oil biodiesel having 5%, 10% and 15% biodiesel. Among the three blends, B10 gave the highest brake thermal efficiency at maximum load. Increased blending of COME resulted in a decrease in CO, NO_x and HC emissions compared to conventional diesel. Dasari et al. further investigated the combustion parameters in the engine cylinder, like the variations in pressure and heat release rate with crank angle and ignition delay. The peak pressure and the net heat release rate were reported to be higher for the biodiesel blended fuels than those for diesel. However, the authors did not explain these behaviour from the basic combustion characteristics of the fuels under consideration.

Notwithstanding the above literature, it may be mentioned that, among different biodiesels, the studies on castor oil biodiesel are still sparse and somewhat contradictory. In order to get a more complete picture on the performance of castor oil biodiesel and its blends with conventional diesel, more extensive research is required on a fundamental level as well as under engine-specific conditions with these fuels. The evaporation and combustion characteristics of the biodiesel can affect engine performance significantly. In view of these, we performed porous sphere droplet combustion experiments with diesel, COME and their blends to compare the performance of the fuels during burning. The fundamental information has been used to analyse engine combustion, performance and emission characteristics of a compression ignition engine running on these fuel blends. Such an approach of investigating the fundamental combustion characteristics to explain the engine performance criteria with the new fuels is the original contribution of the present work.

2. Experimental method and setups

2.1. Biodiesel production

Refined castor oil is collected from the local market in Kolkata, India. Alkaline transesterification is used to prepare biodiesel from castor oil, as the amount of free fatty acids (FFA) in the oil is less than 2% [24,28]. Prior to the biodiesel production, raw castor oil is heated to 80 °C in an air-oven for 2 h to remove any moisture from the oil. For the transesterification process, NaOH (Merck & Co., Inc., USA; minimum assay 97%) is used as the alkaline catalyst along with methanol (Thermo Fisher Scientific, USA; minimum assay 99%). First of all, a methoxide solution is prepared using NaOH pellets (10 g/litre of the oil) and methanol (200 ml/litre of the oil). The castor oil is then mixed with this solution and made to react for 1 h by maintaining a constant temperature of 55 °C at a stirring speed of 500–600 rpm. The resulting solution is then carefully transferred into a separating funnel and allowed to stand overnight. The bottom layer, containing glycerol and other impurities, is then drained out. The remaining part, which is the crude biodiesel, is then washed in a separating funnel with warm water (50% v/v) 4–6 times, until the layer of water at the bottom of the separating funnel turned clear. It ensures that all impurities are completely removed from the biodiesel. Finally, the biodiesel is heated to 80 °C in the air-oven to remove any dissolved moisture. The prepared biodiesel is mixed with diesel (commercial grade) for preparing the fuel blends. Three blends of diesel and biodiesel, with different volume fractions, are used in this experiment — B05 (5% COME + 95% diesel), B10 (10% COME + 90% diesel) and B20 (20% COME + 80% diesel).

The properties of biodiesel depend on the conditions which are maintained during the transesterification process. A thorough characterization of the important properties of the prepared biodiesel has been done, as described in the next section. It may be mentioned here that the biodiesel properties may have been somewhat different with different set of conditions for biodiesel production. However, the present study has primarily focussed on the investigation of the fundamental combustion characteristics, engine performance and emission characteristics with a typical biodiesel, produced from castor oil at one set of conditions, and its blends with diesel. Further investigations can be done on the effects of biodiesels produced at different conditions on the performance of the engine in future.