Crude Castor Oil as Blend Component in Diesel/Ethanol Fuel Blend: Combustion Characteristics and Exhaust Emissions

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Abstract. Some properties such as poor lubricity and low viscosity limit the use of ethanol as an alternative fuel in diesel engines. To improve such inferior properties, crude castor oil with excellent lubricity and extremely high viscosity was added to diesel-ethanol fuel blend. Investigation on combustion characteristics, engine performance and exhaust emissions of a four-stroke single cylinder diesel engine fueled with ternary blend of diesel-ethanol-castor oil was carried out in this research. The blend of 80% diesel, 10% ethanol and 10% castor oil (D80E10C10) was selected for the study. The results on fuel properties showed that the presence of 10% castor oil in diesel-ethanol blend can improve the properties of the blend and meet the diesel fuel specification. The delay in start of combustion was obtained with the use of the ternary blend with respect to diesel fuel combustion, resulting in the lower peak of in-cylinder pressure and temperature. The reduction in nitrogen oxides (NOx) and smoke was found when the engine was operated with the ternary blend at all conditions tested. Carbonaceous gas emissions, carbon monoxide (CO) and unburnt hydrocarbons (HC), was increased with the combustion of ternary blend at low engine operating loads. However, the difference in CO and HC with the combustion of diesel fuel and ternary blend was decreased as the engine loads increased. The addition of crude castor oil to diesel-ethanol blend used as alternative fuel in the diesel engine did not show the significant difference in brake specific fuel consumption and brake thermal efficiency compared to diesel fuel.

1. Introduction
Nowadays, the resources of petroleum used as fuel are depleting with increasing demand, as well as increasingly stringent regulations, pose a challenge to Thailand, which is the non-oil producing country. With the commercialization of bioenergy, it has provided an effective way to fight against the problem of petroleum scarcity and the influence on environment. Although there is an increase in number of literatures to study engine performances and exhaust emissions when using biodiesel, especially in this decade, advanced biofuels such as bio-alcohol and second-generation biodiesel which are derived from waste, agriculture residues and non-food crops have been receiving more attention as sustainable alternative to fossil fuels. Oxygen present in fuel molecules of bio-alcohol and biodiesel can participate in a cleaner combustion process, resulting in a reduction of engine-out emissions to meet increasingly stringent vehicle emission standards. Previous publications have studied the use of diesel fuel blended with ethanol in diesel engines and the results found that the addition of lower 20% ethanol to diesel fuel can be used in diesel engines without any engine modification [1]. It was found that the presence of ethanol in fuel blend participates in the reduction in carbon monoxide [2-3]. More emission benefits of ethanol was obtained due to higher heat of
vaporization which tended to reduce combustion temperature, being less favorable NOx formation [4]. However, the use of ethanol with high percentage as blend component in diesel fuel is not compatible with fuel system and engine components. Fuel containing with high proportion of ethanol is need to improve some key properties. To increase amount of advanced fuel used in vehicles and restore some inferior properties of diesel-ethanol fuel blend, biodiesel derived from castor oil with excellent lubricity and extremely high viscosity was studied [5]. The addition of 10%-15% castor oil methyl ester was enough to improve the lubricity of the diesel-ethanol fuel blend while its viscosity was under the limit of diesel fuel specification. The presence of castor oil methyl ester also increased calorific value, cetane number and flash point of diesel-ethanol blend. Moreover, hydroxyl group belonging to ricinoleic acid (C18:1OH) which is main fatty acid present in castor oil can enhance soot oxidation process. To extend the benefit of castor oil and be more convenient for applying as blend component, crude castor oil was added to diesel-ethanol fuel blend in this work. The physical and chemical properties of ternary blend (diesel-ethanol-castor oil) were studied along with combustion and engine-out emissions and the engine operating with diesel fuel was used as a baseline test.

2. Materials and methods

2.1. Test fuels
The presence of 10% of anhydrous ethanol by volume in the diesel fuel was selected to study the effect of castor oil on fuel properties, combustion characteristics and engine-out emissions. With preliminary work on lubricity experiment, the addition of 10% castor oil was enough to restore the lubricity of the ethanol blends, there was no significant improvement on the blend lubricity after this percentage of castor oil. Consequently, the fuel blend of 10% castor oil, 10% ethanol and 80% diesel fuel (D80E10C10) was used to operate with the engine. The basic physical and chemical properties of test fuels was measured according to ASTM standards and was shown in Table 1. The fatty acid profile of castor oil was detailed in Table 2 and it can be confirmed that the majority of fatty acid present in castor oil is ricinoleic acid with more than 85% wt.

Table 1. Physical and chemical properties of test fuels.

| Fuel Properties                  | Units        | Test Method | Diesel | Ethanol | Castor oil | D80E10C10 |
|----------------------------------|--------------|-------------|--------|---------|------------|-----------|
| Kinematic viscosity at 40 °C     | cSt          | ASTM D445   | 3.54   | 1.26    | 289        | 4.06      |
| Flash point                      | °C           | ASTM D93    | 78     | 13.5    | 282        | 158       |
| Specific gravity at 15.6 °C      | -            | ASTM D1298  | 0.828  | 0.785   | 0.950      | 0.836     |
| Density at 15.6 °C               | kg/m³        | ASTM D1298  | 827.2  | 784.2   | 949.1      | 835.2     |
| Cetane index                     |              | ASTM D976   | 60.18  | 8\(^{CN}\) | 48\(^{CN}\) | 55.2      |
| Gross Calorific Value            | (MJ/kg)      | ASTM D240   | 45.39  | 26.83   | 36.16      | 42.23     |
Table 2. Fatty acid profile of castor oil. (%wt).

| Fatty acid    | % wt |
|--------------|------|
| Lauric       | C12:0| 0.02 |
| Myristic     | C14:0| 0.06 |
| Palmitic     | C16:0| 1.63 |
| Stearic      | C18:0| 1.66 |
| Oleic        | C18:1| 3.85 |
| Ricinoleic   | C18:1OH| 85.6 |
| Linoleic     | C18:2| 6.04 |
| Linolenic    | C18:3| 0.43 |
| Arachidic    | C20:0| 0.08 |
| Gadoleic     | C20:1| 0.58 |
| Eicosadienoic| C20:2| 0.05 |

2.2. Experimental setup
The engine used for this study is a four-stroke, single-cylinder, water-cooled, direct injection compression ignition engine. An eddy current dynamometer with a load cell was used to load the engine. The tests were performed at rated speed of 1500 rpm and three different engine loads (25%, 50% and 75% of maximum engine torque). Commercial diesel fuel was used as a baseline comparison with waste plastic oil for the engine run tests. An air box was used to measure the air flow rate to the engine and volumetric fuel flow rate was measured using a burette and stopwatch. A pressure transducer (mounted on the cylinder head) is connected to a charge amplifier which in turn is connected to computer and a crank angle encoder is used to find crank angle with 1° revolution. The schematic diagram of the test engine setup is given in Figure 1 and the technical specifications of the engine are given in Table 3. The TESTO 350 analyzer was employed to measure nitrogen oxide (NOx), carbon monoxide (CO), hydrocarbon (HC) and TESTO 308 was used to evaluate smoke index. The specification of the gas analyzing device shown in Table 4. At every load, readings were taken after the engine reached steady state. For every refueling, engine was kept running for 10 minutes such that it consumes entire fuel entangled in fuel pipe lines. Repeatability of readings was guaranteed by duplicating the investigations thrice.

![Figure 1. Schematic diagram of the engine test setup.](image-url)
## Table 3. Technical specifications of the engine.

| Engine     | Specification                      |
|------------|------------------------------------|
| Model      | Kirloskar TV1                      |
| Engine type| 1 cylinder, 4 strokes, Water cooled, Direct injection |
| Bore       | 87.5 mm                            |
| Stroke     | 110 mm                             |
| Swept volume | 661 cc                         |
| Rate output | 3.5 kW at 1500 rpm                |
| Compression ratio | 12:1-18:1                     |
| Start of injection | 23 °CA bTDC                  |
| Injection pressure | 210 bars                     |
| Dynamometer | Eddy current                      |

## Table 4. Specification of gas analysing devices.

| Measured quantity | Measuring range | Resolution | Accuracy |
|--------------------|-----------------|------------|----------|
| TESTO 350          |                 |            |          |
| NO                 | 0 to 4000 ppm   | 1 ppm      | ± 5 ppm  |
| NO₂                | 0 to 500 ppm    | 0.1 ppm    | ± 5 ppm  |
| CO                 | 0 to 10000 ppm  | 1 ppm      | ± 5 ppm  |
| HC                 | 100 to 21000 ppm| 10 ppm     | ± 400 ppm|
| TESTO 308          | Smoke index     | 0 to 6     | 0.1      | ± 0.2    |

### 3. Results and discussion

#### 3.1. Engine performance

In the present investigation, experiments were carried out to understand engine performance, combustion characteristics and exhaust emissions of the diesel engine by using diesel fuel and the ternary fuel blend (D80E10C10). The blend was used and the experimental observations were collected so that the results were compared with that of diesel fuel. The engine was loaded in the range of 25%, 50%, and 75% load for a constant speed of 1500 rpm. Figure 2 shows the relation between applied loads and the brake specific fuel consumption. It can be seen that the brake specific fuel consumption decreased as the engine operating loads increased. This was due to the fuel was converted into thermal energy that improved efficiency. The lower brake specific fuel consumption implies that less amount of fuel is needed to generate unit power output. Although, some pore properties of the ternary blend such as higher viscosity and lower calorific value tend to increase brake specific fuel consumption. The better lubricating properties of castor oil can play a role to reduce the power lost by friction [6]. Inversely, brake thermal efficiency increased as the engine operating loads increased (Figure 3). Brake thermal efficiency indicates the ability of combustion system to accept the experimental fuel and provides a comparable means of assessing how efficiently the fuel was converted into mechanical output [7-8]. Brake thermal efficiency increased as engine load increased because more fuel was dispensed with increasing combustion temperature, resulting in high thermal efficiency. Comparing diesel fuel and the ternary blend, the brake specific fuel consumption and brake thermal efficiency was no significant difference between both fuels tested.
3.2. Combustion characteristics

In-cylinder pressure (ICP) and rate of heat release (ROHR) for all engine operating loads are depicted in Figure 4. The first law of thermodynamics was used to calculate the heat release rate with equations (1).

\[
\frac{dQ}{d\theta} = \frac{p}{\gamma - 1} \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta}
\]

where \(\frac{dQ}{d\theta}\) is the rate of heat release, \(p\) is the in-cylinder pressure, \(V\) is the combustion chamber volume, and \(\theta\) is the crank angle. The constant specific heat ratio (\(\gamma\)) of 1.35 was used for the calculation. 100 consecutive engine cycles were performed in order to analyse the in-cylinder pressure and rate of heat release.

Figure 5 shows the combustion characteristics of test fuels. Longer ignition delay (retard in start of combustion) was obtained when the engine was operated with the ternary blend. Low cetane number of ethanol and castor oil together with high heat of vaporization of ethanol can be used to justify the increase in the ignition delay by the combustion of the ternary blend. In addition, lower calorific value of both ethanol and castor oil can participate in lower energy released by the combustion, resulting in lower combustion temperature and in-cylinder pressure. Lower pressure rise in combustion chamber resulted in lower peak of heat release rate.
Figure 5. In-cylinder pressure and rate of heat release.
3.3. Emissions

The formation of nitrogen oxides depends on the temperature in the combustion chamber of the engine. The higher combustion temperature, the higher oxides of nitrogen will be produced. [9] There are also some factors that affect the formation of nitrogen oxides. Combustion of oxygenated fuels such as biodiesel with oxygen contained in fuel molecule, resulting in higher combustion temperature. Low cetane value of fuel causes a long ignition delay, affecting the maximum heat release rate during the combustion of pre-mixed mixtures (premixed combustion). The reduction of oxides of nitrogen can occur by burning fuels with high latent heat of vaporization, such as ethanol, because the fuel that is injected in the combustion chamber will absorb heat to converting liquid to gas phase, resulting in a decrease in combustion temperature. In addition, the high viscosity also affects the temperature in the combustion chamber because the fuel injection into the combustion chamber is a large droplet which leads to lower the temperature in the combustion chamber, leading to lower nitrogen oxides [10].

The results in Figure 5 shows that the combustion of ternary blend produced lower oxides of nitrogen at all engine operating loads. This is mainly due to the higher heat of vaporization of ethanol and high viscosity of castor oil. It is notable that the effect of oxygen content which tends to increase the combustion temperature and be more favorable the formation of nitrogen oxides, was compensated with the effect of low heat of vaporization and high viscosity. Carbon monoxide emissions are dependent on properties of fuel, amount of oxygen, combination of air and fuel, temperature and turbulent air flow in combustion chamber. The results in Figure 7 shows that the slight increase in carbon monoxide was obtained with the use of ternary blend at low and mid engine loads while the reduction in carbon monoxide was found at high engine load, compared to diesel fuel. At low load, temperature in combustion chamber may not be high enough to compensate the effect of high heat of vaporization and high viscosity of fuel blend, resulting in low combustion temperature and less complete combustion. When the engine was operated at high load and temperature in combustion chamber was enough to compensate such effect, lower C/H ratio of ethanol may dominate and lead to the reduction in carbon monoxide by the combustion of ternary blend. Figure 8 shows the variation of unburnt hydrocarbon emissions with engine loads. Hydrocarbons emissions are organic compounds that are caused by incomplete combustion. Higher hydrocarbon was found as engine load increased. This is due to more fuel injected to produce more engine torque and power, resulting in higher possibility of fuel not being burned. Comparing the two test fuels, it was observed that the combustion of ternary blend produced higher hydrocarbon emissions than that of diesel fuel at all engine operating loads. This is likely to be a consequence of high heat vaporization and high viscosity of fuel blend which tends to increase incomplete combustion. Smoke measurement is an indirect way of measuring of diesel particulate emissions. The results in Figure 9 shows that the reduction in smoke index was obtained by the combustion of ternary blend compared to diesel fuel at all engine operating loads. The main reason which can be used to support such reduction is the presence of oxygen in fuel molecules of ethanol and castor oil. Hydroxyl group belonging to both ethanol and ricinoleic acid of castor oil was reported to enhance the soot oxidation and inhibit soot formation [11-12].

![Figure 6. Oxides of nitrogen](image1)

![Figure 7. Carbon monoxide](image2)
4. Conclusions
The study of the use of castor oil with ethanol as an alternative to reducing the use of diesel fuel can be summarized as follows.

- Excellent lubricity and high viscosity of crude castor oil can compensate the loss of such properties of ethanol and the synergic effect was obtained in the study.
- Slight improvement in brake specific fuel consumption and brake thermal efficiency was found when the engine was operated with the ternary blend.
- The combustion of ternary blend showed the delay in start of combustion, lower pressure rise in combustion chamber and lower peak of heat release rate, compared to diesel fuel.
- The benefit in nitrogen oxides and smoke emissions was obtained when the engine was operated with ternary blend at all conditions tested.
- The increase in unburnt hydrocarbon and carbon monoxide emissions were undesirable results for using the ternary blend, especially at low engine operating load.

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

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