Emissions of Jatropha oil-derived biodiesel blend fuels during combustion in a swirl burner

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Abstract. Experimental works on combustion of jatropha oil biodiesel blends of fuel with high swirling flow in swirl burner have been studied in various blends percentage. Jatropha oil biodiesel was produced using a two-step of esterification-transesterification process. The paper focuses on the emissions of biodiesel blends fuel using jatropha oil in lean through to rich air/fuel mixture combustion in swirl burner. The emissions performances were evaluated by using axial swirler amongst jatropha oil blends fuel including diesel fuel as baseline. The results show that the B25 has good emissions even though it has a higher emission of NOx than diesel fuel, while it emits as low as 42% of CO, 33% of SO2 and 50% of UHC emissions with high swirl number. These are due to the higher oxygen content in jatropha oil biodiesel.

1. Introduction

Researches on biodiesel combustion are widely studied all over the world using different kinds of combustion methods and various types of feedstock to apply in transportation, power plant, boiler, furnaces and etc [1-6]. Combustion of biodiesel is being explored as part of the quest to reduce the emissions from diesel-fuelled vehicles either using neat biodiesel or by blending the biodiesel with fossil fuel [7, 8]. Biodiesel is used as an alternative fuels because it’s biodegradable, renewable, non-toxicity, less pollution forming and aromatic [9, 10]. Biodiesel is produced from the fatty acids triglycerides containing three fatty acid molecules and a glycerol molecule, produced either from vegetable oils, animal fats or waste oils via the transesterification method [11, 12]. Biodiesel is also referred to as a mono alkyl ester that is produced from vegetable oils, including the edible and non-edible oils. The edible oils are including palm, soybean, rapeseed, sunflower, canola, corn and coconut while the non-edible oil are produces from jatropha, castor, karanja, pongamia and rubber [13, 14].

Jatropha oil is a potential low-cost biodiesel feedstock and is extracted from the jatropha seed, which has a high oil content and potential of high-seed yield per land area [15, 16]. This plant which naturally grows in tropical countries such as in Africa, Mexico, and India, is used as biodiesel feedstock because it is easy to grow and cheap to plant [17]. The oil consists of a series of saturated and unsaturated acids, includes major groups of fatty acids, and has good oxidation stability and low viscosity [11]. In order to produce biodiesel, jatropha oil is put through the common procedure of
homogeneous catalyzed transesterification process, specifically alkaline-catalyzed transesterification. However, this method is not efficient if the amount of free fatty acids (FFAs) in the oil do not exceed 1% by weight. Conversely, if the FFA exceeds 1% wt, the extra step of the biodiesel production must be applied, which is the esterification process. As reviewed in many studies, the non-edible oil contains high FFA and required to be esterified before throughout the esterification and transesterification methods [18]. Many studies have attempted to use the combination of acid-catalyst esterification and alkaline-catalyst transesterification to complete the production of biodiesel. Catalyst needs to be presented in both methods to increase the reaction rate and yield of biodiesel [19].

Significantly, biodiesel fuels produced less gas emissions of gases such as carbon monoxide (CO), sulfur oxide (SO), unburned hydrocarbon (UHC), soot, and aromatics. They also increased the uniformity of air-fuel mixing and higher intrinsic oxygen content [20, 21]. But conversely, they produced slightly increased NOx emission due to high combustion temperature. The NOx emission promises to be less in diesel engines at lower temperature combustion [21, 22]. In case of neat biodiesel combustion, the CO emission can be reduced by increases the air preheat temperature. Rehman, et al. [23] reported that higher viscosity of jatropha biodiesel can be reduced by blending with diesel fuel. CO and UHC emissions from gas turbine combustion obtained from B15 and B25 blends are lower than from diesel fuel due to complete combustion with oxygenated biodiesel blend fuels. Conversely, NOx emissions for blends of both biodiesels are higher due to higher flame temperature. Bhale et al. [24] observed that kinematic viscosity of Madhuca methyl ester (MME) where the oil was obtained from Madhuca indica has about 1.6 times higher than diesel fuel at 40°C. Hashimoto et al. [25] in studies on the combustion characteristics of palm oil biodiesel for gas turbines engine found that the palm methyl esters (PME) has similar results compared with diesel fuel results indicated that NOx emissions could be reduced with increasing excess air ratio. A few researchers agreed that combustion efficiency can be enhanced by using biodiesel fuel because of the structure providing a higher oxygen content of the fuel [20, 26]. Reddy et al. [27] has explored the combustion of biodiesel and its blends with diesel at a 50% ratio in a high swirl and low emission burner. The blend was combusted with and without air preheating at different temperature of 623, 673 and 703 K. It found that neat biodiesel combustion produced higher NOx, CO and HC emissions than the biodiesel blends. Inversely, it showed that biodiesel blend fuel helps in reducing the NOx and HC emissions.

The purpose of this study was to evaluate the emission characteristics of jatropha oil biodiesel (JBD) blends in various percentages with diesel fuel using a swirl burner. The potential use of JBD and its blends in swirl burner can thus be determined and assessed from this study.

2. Materials and Methods

2.1 Materials and Chemicals

The crude Jatropha curcas L. oil used in this work was obtained from Bionass Sdn Bhd with a high FFAs content (22.5%), which for production of biodiesel requires esterification and transesterification process, due to long-chain fatty acid value in triglycerides. All chemicals used in the experiments and analyses were obtained in their analytical grade. Sulphuric acid (H2SO4) was used as the catalyst with methanol for the esterification process, while potassium hydroxide (KOH) was the base catalyst selected to enhance the reaction for the second step, being the transesterification process. Experiments to produce the biodiesel were conducted in a laboratory-scale setup developed at the Gas Turbine Combustion Research Group (GTCRG) laboratory at the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

2.2 Biodiesel Production Procedures

The first step in the production of biodiesel from jatropha oil was the esterification process. The 300 mL of jatropha oil was heated in a three-neck flask (500 mL) to 60°C. Then, the molar ratio at 12:1 (50% v/v oil) of methanol was measured and added into the pre-heated oil followed by 1% (m/m oil) of H2SO4. This process used a thermometer, mechanical stirrer and reflux condenser to condense the
methanol escaping from the reaction mixture, using 400 rpm stirring speed for 3 hours at 60°C. After the esterification process was completed, the reaction oil was poured into a separation funnel for 2 hours to separate the oil and excess alcohol with H$_2$SO$_4$. The lower layers of jatropha oil biodiesel were put into a three-neck flask and the acid value was found to be less than 3 mg KOH/g oil.

After completion of the esterification process, the most common method to complete the production of biodiesel is by a homogeneous transesterification process. The triglyceride obtained from the initial esterification process was reacted with 25% (v/v oil) methanol (or 6:1 molar ratio) and 1 wt% (m/m oil) catalyst of KOH at 60°C. The triglyceride, alcohols and catalyst of KOH were reacted in the same equipment used in the previous process under reflux for 2 hours and 400 rpm stirring speed. Then, the products were poured in separation funnel up to 12 hours to separate the biodiesel and glycerol. The glycerol with impurities that made up the bottom layer was drawn off.

The methyl esters formed in the transesterification process continued into the post-treatment of washing it with warm (50°C) distilled water five times to remove the excess alcohol, catalyst and remained glycerol. The ratio of distilled water to biodiesel was 2:1. The process continued with heated of the liquid up to 110°C and stirring of the methyl ester into the Erlenmeyer flask to remove the moisture and remaining methanol. Finally, the JBD was blended with the diesel fuel in various percentages, initially as B10 till B25. The characterization of JBD properties have been done according to ASTM standard as mentioned in Table 1.

### 3. Experimental Works

The combustion of biodiesel and biodiesel blends fuel was set up using the combustion rig and gas analyzer. The rig was built up with the fuel line system, airflow system, igniter, nozzle, axial swirler, combustion chamber and gas analyzer system as shown in Fig. 1. The fuel flow rate was fixed for each case as measured and with the appropriate nozzle used. The fuels were sprayed throughout the nozzle at pressure of 16 bars approximately. The air mass flow rate was controlled by control box and flowmeter was used to measure equivalence ratios from lean to rich mixture. When the burner was switched on, the air mass flow rate was displayed on flowmeter and combustion occurred horizontally inside the combustion chamber. Then, the data of emissions and temperature was recorded. This analyzing system of combustion products was using the ENDA-5000 series of stack-gas analyzer system manufactured by Horiba. The system measured the NO$_x$, SO$_2$, CO, carbon dioxide (CO$_2$) and oxygen (O$_2$) of dry flue gases accurately in real time. The exhaust temperature was measured at the end of chamber using a thermocouple attached to the data logger.

| Parameter                          | Diesel | JOME |
|------------------------------------|--------|------|
| Density (g/m$^3$)                  | 0.835  | 0.8717 |
| Viscosity at 40°C (mm$^2$/s)       | 3.619* | 4.521 |
| Acid value (mg KOH/g)              | 0.06** | 0.515 |
| Flash point (°C)                   | 77*    | 170  |
| Pour point (°C)                    | -20*   | -6   |
| Cloud Point                        | -35*   | 6    |
| Cetane number                      | 48*    | 54.8 |
| Calorific value (MJ/kg)            | 45.2*  | 39.7 |
| Cold Filter Plugging Point (°C)    | -1     |      |
| Oxidation Stability, 100°C         | -      | 2.1  |
| Total sulfur (mg/kg)               | 310**  | 1.8  |
| Carbon content (%wt)               | -      | 76.7 |
| Hydrogen content                  | -      | 12.6 |
| Nitrogen content                   | -      | <0.1 |
| Oxygen content                     | -      | 10.8 |

Refer to *Abedin, Masjuki [28] and **Ng and Gan [9]
4. Results and discussion

The combustion products are produced in varying amounts depending on the type of fuels, either from fossil fuels or biofuels like biodiesel. This study focuses on emissions from biodiesel blend fuels to attempt to meet the “greener” environmental criteria for emissions. In this case, the various percentages of biodiesel fuels were blended with diesel fuel to locate the optimum biodiesel percentages which should be used. The emissions of NO\textsubscript{x}, CO, SO\textsubscript{2}, and UHC of each blend percentages were evaluated and compared with the figures from diesel fuel. In this case, the emissions of each fuel were studied in the lean condition of combustion using the swirl burner. Four different percentages of JBD blend fuels were prepared. There are denoted as JBD B10, JBD B15, JBD B20 and JBD B25 respectively, where the numerical value denotes biodiesel percentage in the blends.

NO\textsubscript{x} emissions of JBD blend fuels are higher compared to diesel fuels as shown in Fig. 2. Overall, the results show almost similar trends of NO\textsubscript{x} emissions, in that increasing the percentages of blends raised the NO\textsubscript{x} emissions. This phenomenon happened due to higher viscosity of biodiesel compared to diesel fuel has lower viscosity. When the blended fuel has high viscosity, the droplet size is much larger and causes the poor atomization in the spray vaporization.

At higher biodiesel percentages, the NO\textsubscript{x} emissions are getting higher than diesel. But as shown in graph, the JBD B20 is higher than JBD B25 but it is not significantly different, while JBD B10 produced figures showing a similar amount of NO\textsubscript{x} emissions as diesel fuel near the stoichiometric mixture. JBD is an oxygenated fuel, the higher oxygen availability than in diesel fuel is likely to be the cause of higher NO\textsubscript{x} in the chamber. In this case, the oxidation of nitrogen is improved with the presence of more oxygen in JBD and increased the flame temperature during combustion period. Moreover, the methyl esters lead to uneven air-fuel mixing and high temperature in the flame due to poor atomization and vaporization.
Fig. 3 presents the CO emissions of JBD blend fuels in relation to equivalence ratio, $\phi$. The CO emissions decreased as $\phi$ increased. In the case of studies, the mass flow rate of fuel was set to be constant while the air flow was adjusted according to the $\phi$ required. Overall, all JBD blends fuel emitted less CO than diesel fuel under overall $\phi$ except for JBD B10 which is higher. Higher CO emission from diesel fuel is due to higher carbon content in diesel fuel. The trends of CO emissions show a decrease from lean to rich mixture of combustion due to the higher proportion of air extinguishing the flame and the temperature in flame drops. Of the blends JBD B10 has higher CO emission caused by more carbon content in diesel fuel relative to low percentage of biodiesel in the blends. It also might be due to poor atomization and non-uniform fuel distribution during combustion specifically at $\phi$ of 0.8 towards 1.0. As noted, the higher oxygen content of biodiesel (comprising about 11% wt of O$_2$) can be expected to result in reduced CO emissions and more complete combustion [29]. In summary, higher percentage biodiesel blend fuels had given the lower CO emission compared to diesel fuel. But the trend of CO emissions of each blends and diesel fuel are effectively the same.
Fig. 4 shows \( \text{SO}_2 \) emissions of JBD blend fuels reduced with increase of percentage of biodiesel in the JBD blends, compared with diesel fuel. Consequently, from lean to stoichiometric state, JBD blends were presented increasing on \( \text{SO}_2 \) emissions. The \( \text{SO}_2 \) emissions show the similar trend for each fuel. Diesel fuel achieved up to 14 ppm in stoichiometric state while JBD blends have 11 to 12 ppm. \( \text{SO}_2 \) emission depends on the sulfur content in each type of fuel. Fig. 4 shows that the biodiesel blends emitted lower amounts of \( \text{SO}_2 \) emissions, which indicate sulfur is contained in diesel fuel. In fact, biodiesel is known as sulfur-free or less sulfur compared to fossil fuel. Otherwise, the small amounts of sulfur in flue gases of biodiesel might be produced during esterification interaction from methanol and \( \text{H}_2\text{SO}_4 \). Significantly, from the lower \( \text{SO}_2 \) emissions in this study, biodiesel is more suitable for combustion in a swirl burner.

**Figure 4.** Emissions of \( \text{SO}_2 \) for various JBD blends fuel.

**Figure 5.** Emissions of UHC for various JBD blends fuel.
Emission on unburned hydrocarbons (UHC) for biodiesel blends of fuel were lower compared with diesel due to higher oxygen in biodiesel fuels as shown in Fig. 5. It was expected that more complete combustion would be seen with the biodiesel blends, and the diesel engine had higher UHC emissions in the flue gas output. In summary, the higher UHC emissions on biodiesel blends were observed in lean state and it was getting lower to nearly zero towards stoichiometric. It was caused by increment of air flow rate, and the UHC emission of diesel fuel also showed this reducing trend.

5. Conclusion
The experimental data of emissions obtained from JBD blends varying from lean towards stoichiometric mixture of combustion at $\phi$ range of 0.6 to 1.3. Overall, NO$_x$ emissions for all blends of biodiesel were increased due to high oxygen content in biodiesel fuel. Overall, the emissions produced in flue gases from combusting the different blends of biodiesel have similar trends compared with emissions from diesel fuel when using the swirl burner. Therefore, JBD B25 helps to significantly improve on CO, SO$_2$ and UHC emissions by 42%, 33% and 50% respectively. JBD B25% is viable as an alternative fuel to reduce emissions towards greener environmental.

6. References
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