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Waste Cooking Oil Biodiesel via Hydrodynamic Cavitation on a Diesel Engine Performance and Greenhouse Gas Footprint Reduction

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The performance and emission characteristics of conventional diesel fuel and biodiesel blends of 20, 40 and 50 % from waste cooking oil (WCO) based on hydrodynamic cavitation (HC) have been compared and found to be acceptable according to the EN 14214 and ASTM D 6751 standards. The tests have been operated in an In-line vertical six cylinder diesel engine at different engine speeds ranging 1,000 to 2,000 rpm under full throttle load. The experimental results showed that biodiesel blends had higher brake specific fuel consumption (3.8 - 9.0 %) and exhaust gas temperature (2.3 – 6.8 %), while lower brake power (2.6 – 6.7 %), torque (1.4 – 5.2 %) and brake thermal efficiency (3.7 – 8.4 %) than diesel fuel. Engine emissions showed higher CO_2 (18.8 – 38.5 %) and NOx (7.5 – 19.0 %), but remarkable decreased of CO (6.8 – 26.3 %) compared to diesel fuel. Higher CO_2 is emitted, but it is greatly reduced from the view of the life cycle circulation of CO_2 (carbon footprint). Low cost of WCO through HC is a simple scale up, energy efficient, time saving and eco-friendly make biodiesel viable for industrial production and also can be used without any engine modifications as an alternative and environmental friendly fuel.

1. Introduction

Pure biodiesel has low SOx emissions during the combustion in diesel engines as the S content can be ignored. Sanjid et al. (2013) has reviewed sources of diesel engine performance fuelled by biodiesel derived from different feedstock oil compared to diesel fuel. They found that most researchers claimed brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) increased, whereas brake thermal efficiency (BTE), torque and brake power (BP) decreased using biodiesel compared to diesel fuel during combustion in a diesel engine. Xue et al. (2011) have reviewed the works on the emission characteristics of biodiesel in a diesel engine compared to diesel fuel, in which the majority of the researchers claimed that the emission of NOx increased. However, CO_2, CO and hydrocarbon decreased using biodiesel compared to diesel fuel during combustion in a diesel engine. A minority of researchers claimed conversely that the biodiesel and diesel fuel give an equivalent and opposite CO_2, CO and hydrocarbon emissions. An et al. (2013) reported that some researchers claim biodiesel emitted lower CO_2 due to a lower carbon to hydrogen ratio and the presence of an O atom compared to diesel fuel. The opposite trend has been found by other researchers: Kalam et al. (2011) claimed that biodiesel emitted higher CO_2 emissions due to complete combustion, which more CO is converted into CO_2. On the contrary, Pleanjal et al. (2009) reported that biodiesel could result in a 50 – 80 % reduction of CO_2 emissions compared to diesel fuel. Biodiesel of 0.002 - 0.007 wt.% contains 2 to 20 fold higher nitrogen content compared to petroleum diesel of 0.0001 - 0.003 wt.%, which emits NOx during combustion (Sun et al., 2010). This can cause acid rain and other harmful effects. Considerable research has

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been performed to remove nitrogen in biodiesel by using a hydrogenating process. However, this process has proved costly. NOx emissions can be alternatively reduced by various measures such as the deNOx method.

Biodiesel is one of the alternative renewable fuels, which can be produced from various sources including edible oil, non-edible oil, animal fat and algae (Chuah et al., 2015a). About 95 % of world biodiesel production is derived from edible oils (Bokhari et al., 2016). It has been strongly opposed by non-government organisations worldwide due to its negative impact as it competes with food for resources (Chuah et al., 2015a). Malaysia is diversifying its biodiesel feedstock towards non-edible oil, such as WCO derived from palm oil. This country is the second largest producer of palm oil in the world. Around 0.12 Mt/y of WCO is produced there. Minimising the Carbon Footprint or better Greenhouse Gas Footprint (Lam et al., 2010) of biodiesel needs to take into account that it is an advantage to utilise it in local regions rather than export to other regions. WCO is even cheaper - on average five times lower cost than refined cooking oil (RCO). Biodiesel derived from waste oil can be a very promising alternative feedstock, which could reduce the production cost and global emission management cost as a lower pollutant emission.

Various intensification technologies, i.e. super critical condition, microwave (Bokhari et al., 2015), ultrasonic cavitation (UC) and HC (Yusup et al., 2015) have been applied by many researchers to eliminate the mass transfer resistance of immiscible reactants in shorter reaction times and lower energy consumption compared to commonly used mechanical stirring (MS). HC is the most efficient technology to provide a substantial promise for biodiesel production in terms of high ester conversion, shorter reaction time and high yield efficiency. This is a greener and cleaner intensification process that based on energy efficient, shorter reaction time, cheap and renewable raw materials. HC has been widely used in wastewater treatment and the shipping industry, but only a few works have reported use in the biodiesel field since 2006. Only Pal et al. (2010), who have studied the performance of diesel engine fuelled by biodiesel derived from thumba oil using HC. However, a few papers have focused on emissions in a compression ignition diesel engine. Performance and emission of diesel engine fuelled by biodiesel are influenced by its properties, such as viscosity, density, cetane number (CN), calorific value, fatty acid composition, O and S content. In this study, biodiesel from WCO was produced in a HC reactor via transesterification under optimised conditions. Waste cooking oil methyl ester (WCOME) properties were also analysed according to the ASTM D 6751 and EN 14214. Different blending ratios of WCOME, i.e. B0, B20, B40 and B50 were used in the diesel engine in order to study the performance and emission characteristics.

2. Materials and Methodology

2.1 Materials

The detail of the collected WCO was reported in Chuah et al. (2015b). The properties of WCO had been reported in previous paper (Chuah et al., 2015c). The diesel fuel was purchased from Heng Hooi Chee Sdn Bhd. The chemicals used for this work were reported in paper (Chuah et al., 2015d).

2.2 Biodiesel production

The HC reactor with a 50 L capacity is connected to the diaphragm pump in a closed loop called the batch reactor. The detail of the WCOME production was reported in previous paper (Chuah et al., 2015c).

2.3 Biodiesel Blending

Biodiesel blends were prepared by using an electric homogeniser. The homogeniser was fixed on a vertical stand by a clamp and rotated at 2,000 rpm for 30 min to mix the biodiesel blends in order to ensure homogeneity (Ong et al., 2014). The B20, B40 and B50 were prepared base on volume basis, e.g. 20, 40 and 50 % of WCOME were mixed with diesel fuel (B0).

2.4 Test Fuel Properties

Physicochemical properties of WCOME, diesel fuel, B20, B40 and B50 were measured at the Biomass Processing Laboratory, Universiti Teknologi PETRONAS. The biodiesel properties were analysed according to the ASTM, EN, DIN and AOCS standards as mentioned in Chuah et al. (2015a). Each of tests was conducted in three replicates and the reported values are averages of the individual runs and the inaccuracy percentage were less than 2 % of the average value.

2.5 Experimental Setup for Performance Testing

The experiment was carried out using an In-line vertical six-cylinder with four stroke engine. The more detail information of experimental setup had been reported in previous paper (Chuah et al., 2015b). The main aim of this experiment is to investigate the diesel engine performance and emission fuelled by biodiesel blends, which was produced via HC in comparison to those produced by diesel fuel.

3. Results and Discussion

3.1 Biodiesel Properties Analysis Produced Through Hydrodynamic Cavitation

It is observed that the acid value increased with the rising of biodiesel blending ratio. Acid value of pure biodiesel (B100) was 0.30 mg KOH/g and about 100 fold higher than diesel fuel (B0), e.g. 0.003 mg KOH/g. The kinematic viscosity of WCOME was 4.62 mm^2/s and satisfied EN 14214 standard at temperature of 40 °C. Consequently no further modification of diesel engine is needed as there is no significant difference compared to the viscosity of diesel fuel, i.e. 3.65 mm^2/s. The obtained heating value for WCOME was 39.99 MJ/kg and this value was lower than diesel fuel, which was recorded to be 45.39 MJ/kg. The heating values of blended biodiesels ranged from 42.43 to 44.38 MJ/kg. CN is an ability of the fuel to ignite quickly after being injected and a higher value indicates better ignition quality of the fuel. CN in the present study was found to be 60 for pure biodiesel, which is within the standards. CN increased with an increase of biodiesel blending ratio.

3.2 Performance Analysis

3.2.1 BP

The variation in engine BP output with engine speed for all tested biodiesels and diesel fuel at constant 100 % throttle position is illustrated in Figure 1. It was found that a similar trend of BP in blended biodiesel and diesel fuel, which increased as the engine speed increased from 1,000 rpm until it reached maximum value at 1,900 rpm. Beyond this engine speed, it decreased due to the effect of higher frictional force (Liaquat et al., 2013). It was observed that maximum BP of B0 was 284 kW at 1,800 rpm. All the tested biodiesel blends tend to give lower maximum BP (267 to 278 kW) at higher engine speed of 1,850 rpm compared to diesel fuel. Higher engine speed is required for all biodiesel blends to reach maximum engine power. This could be attributed to a lower energy content, higher density and viscosity of biodiesel than diesel fuel, which resulted in low combustion efficiency, poor atomisation and poor mixture formation. It agreed well with Tuccar et al. (2014), the BP reduction could be attributed to low calorific value in biodiesel.

3.2.2 Torque

Figure 2 describes the variation of torque with respect to the engine speed for diesel fuel and biodiesel blends of WCO. In case of WCOME blends and B0, maximum torque values remained almost constant from 1,000 until 1,300 rpm and then started to decrease with further increasing of engine speed up to 2,000 rpm. It was found that the torque of biodiesel blends was generally lower than diesel fuel. Maximum torque of B0 was 1,735 Nm at 1,200 rpm. All the tested biodiesel blends tend to give lower maximum torque at lower engine speed of 1,150 rpm compared to diesel fuel. This is mainly due to the reduction in lower heating value of biodiesel as explained by Liaquat et al. (2013). Ong et al. (2014) also claimed that torque reduction increased with increasing blending ratio of biodiesel due to its higher density and viscosity. Higher O contents of WCOME also lead to decrease torque compared to diesel fuel as reported by Tuccar et al. (2014).

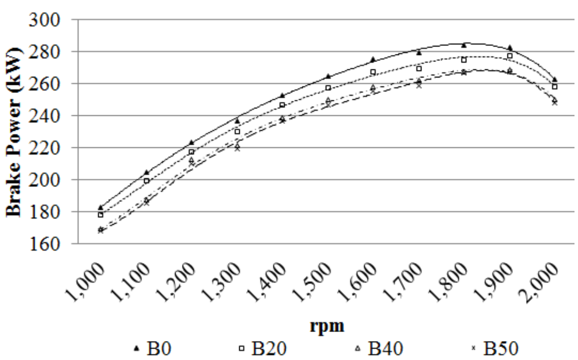

Figure 1: Variation in BP with engine speed

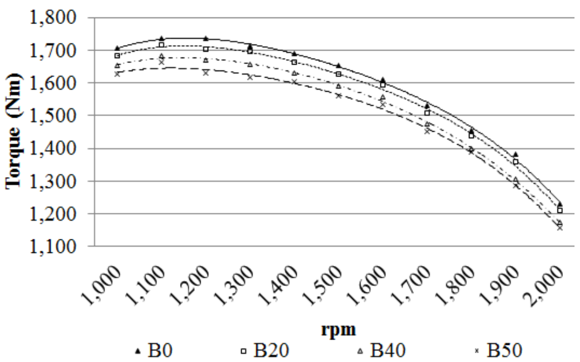

Figure 2: Variation in torque with engine speed

3.2.3 BSFC

BSFC is an indicator of the loss of heating value (Lapuerta et al., 2008). Figure 3 portrays the nature of BSFC for all tested fuels as a function of engine speed at full load was within a narrow range. It was found that the BSFC of biodiesel blends trend was higher than diesel fuel. BSFC of each tested fuels was almost the same between 1,200 and 1,900 rpm. An increase of BSFC could be due to higher density of biodiesel blends, more biodiesel blend fuels by mass were injected into the combustion chamber compared to the amount of diesel fuel injected (Ozener et al., 2014). When further increased in the O content from B20 to B50 then BSFC increased an average about 5 % over the entire speed range. Biodiesel contained O resulted in lower heating value and the same energy output from the engine required larger mass fuel flow which increased BSFC to compensate the reduced chemical energy in the fuel as explained by Rizwanul Fattah et al. (2014). Higher kinematic viscosity of biodiesel blends may cause poor atomisation of the fuel and consequently poor mixing with air resulted in higher BSFC as agreed with Abedin et al. (2014). BSFC of biodiesel blend fuels (B20 - B50) increased from approximately average of 223.5 to 234.7 g/kWh as the brake mean effective pressure decreased from approximately average of 16.4 to 15.8 bar. However, result of BSFC trend in comparison between biodiesel blends and diesel fuel reported by Pal et al. (2010) is in contrast with this study.

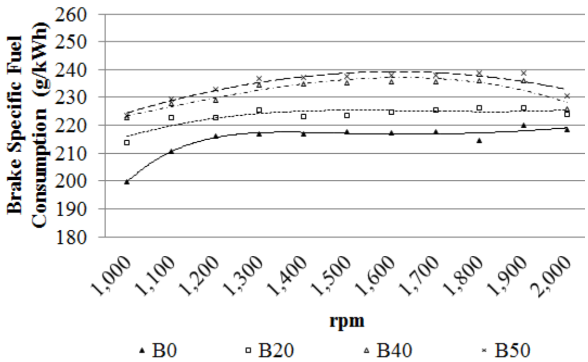

Figure 3: Variation in BSFC with engine speed

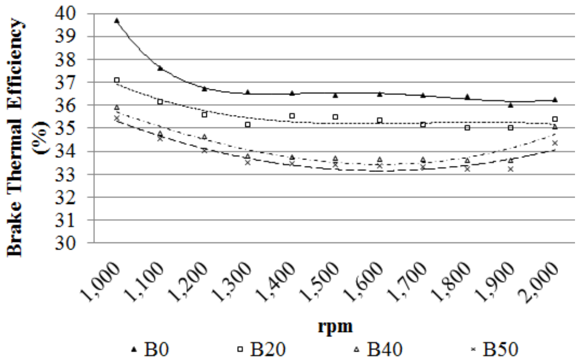

Figure 4: Variation in BTE with engine speed

3.2.4 BTE

BTE is the ratio of BP to the energy released during the combustion process. The variation of BTE with engine speed for all the tested biodiesels and diesel fuel is in Figure 4. It can be observed that almost similar behaviour of BTE with the diesel fuel for all biodiesel blends. Maximum BTE values for all blends and diesel fuel were at 1,000 rpm and then started to decrease with further increased of engine speed up to 1,900 rpm, but again slightly increased at 2,000 rpm. It was found that BTE of biodiesel blends is slightly lower than diesel fuel over entire engine speed. BTE of diesel fuel (36.7 %) was higher than biodiesel blends (34.0 to 35.6 %) when maximum torque reached at 1,200 rpm. However, slightly lower BTE of diesel fuel (36.4 %) compared to biodiesel blends (33.2 to 35.0 %) when maximum BP reached at 1,800 rpm. This could be attributed to lower heating value, higher density and viscosity of WCOME which lead to poor atomisation and fuel vaporisation.

3.2.5 EGT

EGT is an indication of the cylinder combustion temperature and engine lifespan. EGT may vary slightly as different engines are made from different alloys that have varying heat properties. The variation of the nature of EGT for all tested fuels as a function of engine speed at 100 % throttle position is depicted in Figure 5. The EGT raised with an increase of engine speed for diesel fuel and biodiesel blends. The fuel blends behaviour of EGT was higher than diesel fuel due to its higher calorific value and O content (Ong et al., 2014).

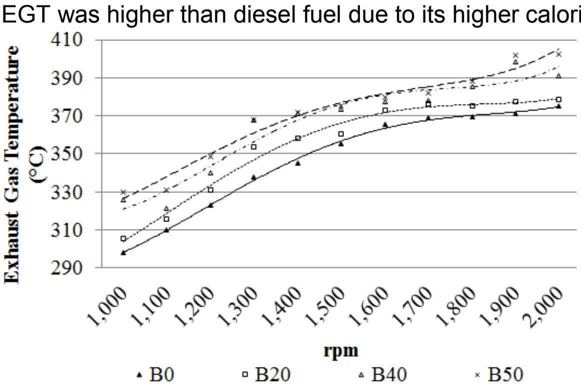

Figure 5: Variation in EGT with engine speed

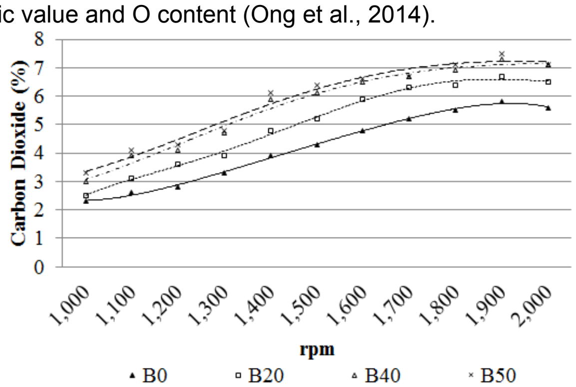

Figure 6: Variation in CO_2 emissions with engine speed

3.3 Emission Analysis

3.3.1 CO_2

Amount of CO_2 is an indication of complete combustion of fuel test inside the engine cylinder. A comparison of CO_2 emission between diesel fuel and biodiesel blends is exhibited in Figure 6. It can be noted that the CO_2 emissions increased with an increase in the biodiesel blends ratio compared to diesel fuel. The biodiesel blends showed higher CO_2 emissions than diesel fuel due to the O content in its blends, which reacted with unburned carbon atoms during the combustion and hence increased the formation of CO_2 as elucidated by

Liaquat et al. (2013). Biodiesel blends emitted higher CO_2 emissions as its blends gave more time for complete combustion and hereafter more CO were converted into CO_2 (Xue et al., 2011). Although increased of CO_2 emissions was observed during combustion by using biodiesel blends, it is greatly reduced from the view of the life cycle circulation of CO_2 and the CO_2 level is kept constant in the atmosphere.

3.3.2 CO

CO is a toxic gas formed during incomplete combustion due to the flame front approaches the crevice volume and relatively cold cylinder liner (Sanjid et al., 2013). The variations of CO produced by running the diesel engine using diesel fuel and biodiesel blends are illustrated in Figure 7. It was found that a similar trend of CO in biodiesel blends and diesel fuel, which deceased as the engine speed increased from 1,000 rpm until it reached a minimum value at 2,000 rpm. It was noted that CO emissions of diesel fuel are higher than biodiesel blends. This was due to biodiesel blends contained more O element, which gave better combustion (Rizwanul Fattah et al., 2014). Low CN value resulted in ignition delay time increased and allowed limited combustion time duration for complete reaction (Tuccar et al., 2014). Tan et al. (2013) claimed that CO emissions reduced when the S content decreased. During combustion, S consumed O in local area, thus affected the CO further oxidation. This result contradicted with Ong et al. (2014) who investigated that *Ceiba pentandra* methyl ester and *Calophyllum inophyllum* methyl ester blends fuel emitted higher CO than diesel fuel at full load. On the other hand, Ozener et al. (2014) claimed that most literatures agreed that lower CO emissions during combustion of biodiesel compared to diesel fuel utilisation.

3.3.3 NOx

NOx formation strongly dependents on in-cylinder temperature and pressure. NOx emissions versus engine speed at constant full throttle load are depicted in Figure 8. NOx emissions from biodiesel blends were found to be higher than diesel fuel. It could be attributed to O content and CN increased with increasing biodiesel blends ratio compared to diesel fuel. Ozener et al. (2014) also stated that higher O content in biodiesel blends is responsible for NOx formation because it caused the local temperature to increase and then resulted in an excess hydrocarbon to be oxidised. This agreed well with this study when the temperature increased in combustion chamber with an increase of blending fuel, resulted in greater NOx emissions compared to diesel fuel. Rizwanul Fattah et al. (2014) stated that biodiesel is an oxygenated fuel and possessed a shorter ignition delay due to higher CN. In this study, the tested fuel attained maximum value of NOx at 1,900 rpm and caused higher heat (i.e. maximum BP) released and resulted in higher temperature in the engine cylinder. This also promoted the NOx formation.

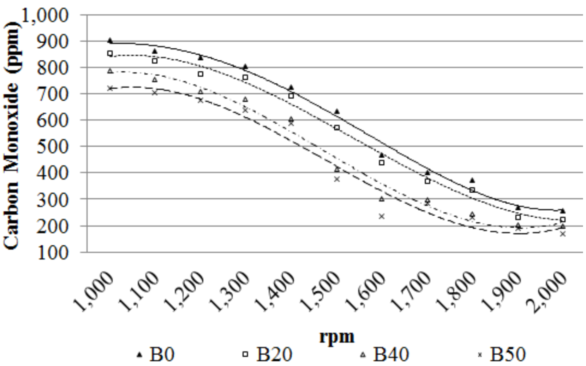

Figure 7: Variation in CO emissions with engine speed

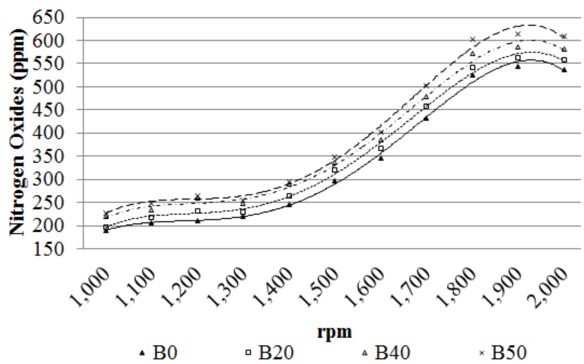

Figure 8: Variation in NOx emission with engine speed

4. Conclusions

The properties of WCOME produced from HC reactor conform to both standards of EN 14214 and ASTM D 6751. In terms of engine performance, biodiesel blends compared to diesel fuel provide the following results: slightly higher of BSFC and EGT, whereas slightly lower of BP, torque and BTE were. With regard to the engine emissions, higher CO_2 and NOx, whereas significantly decrease in CO. Although biodiesel blends emitted higher CO_2 during combustion compared to diesel fuel, they greatly reduced circulation of CO_2 when analysed over the life cycle. The increase of NOx emissions in biodiesel blends during combustion compared to diesel fuel could be solved by various measures of the deNOx method.

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