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MITIGATION OF NO_X AND CO EMISSIONS FROM LIQUID FUEL BURNER FIRING JATROPHA BIODIESEL BLENDS

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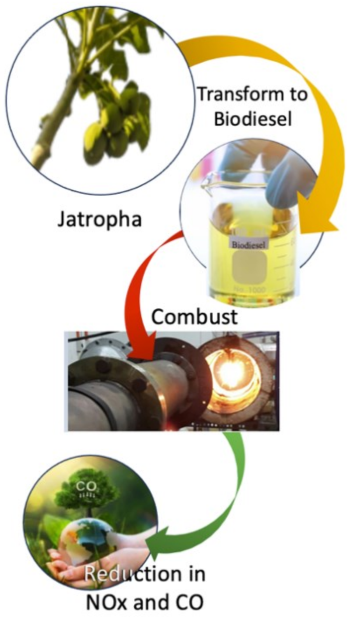
Graphical abstract



Abstract

This paper highlights the comparison of emission characteristics of Nitrogen Oxides (NO_X) and Carbon Monoxide (CO) as well as the combustor wall temperature profile when firing various Jatropha Methyl Ester (JME) biodiesel blends, B5 (5% JME, 95% CDF), B15 (15% JME, 85% CDF) and B25 (25% JME, 75% CDF) with Conventional Diesel Fuel (CDF). The properties of the fuels tested were determined and compared with CDF. All tests were carried out at three different combustion conditions: lean, stoichiometry and rich; with equivalence ratio between 0.8 and 1.2. The formation of NO_X and CO emissions from JME biodiesel fuels were reduced and generating lower wall temperature profiles than CDF across all equivalence ratios. The increase in JME content from B5 to B25 significantly improved the reduction of both emissions gases and the wall temperature profiles. The findings suggested that JME biodiesel has the potential to reduce the dependency on CDF, since the properties are similar to CDF fuel and hence, resulting in lower NO_X and CO emissions without significantly compromising the heat generated from combustion. This would be beneficial for industries to utilize a cleaner, safer and sustainable biodiesel fuel for their energy generation.

Keywords: Jatropha methyl ester, conventional diesel fuel, properties, combustion, emission

Abstrak

Kertas kerja ini menekankan perbandingan ciri-ciri pelepasan Nitrogen Oksida (NO_X) dan Karbon Monoksida (CO) serta profil suhu dinding pembakar semasa pembakaran pelbagai campuran biodiesel Jatropha Methyl Ester (JME), B5 (5% JME, 95% CDF) , B15 (15% JME, 85% CDF) dan B25 (25% JME, 75% CDF) dengan Bahan Api Diesel Konvensional (CDF). Sifat bahan api yang diuji telah ditentukan dan dibandingkan dengan CDF. Semua ujian telah dijalankan pada tiga keadaan pembakaran yang berbeza: kurus, stoikiometri dan kaya; dengan nisbah kesetaraan antara 0.8 dan 1.2. Pembentukan pelepasan NO_X dan CO daripada bahan api biodiesel JME telah berkurang, menghasilkan profil suhu dinding yang lebih rendah daripada CDF pada semua nisbah kesetaraan. Peningkatan

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kandungan JME daripada B5 kepada B25 telah mengurangkan kedua-dua pelepasan dan profil suhu dinding dengan ketara. Penemuan ini mencadangkan bahawa biodiesel JME berpotensi untuk mengurangkan pergantungan pada CDF, kerana ciri-cirinya adalah serupa dengan bahan api CDF. Oleh itu, pelepasan NO_X dan CO yang lebih rendah tanpa menjejaskan haba yang dijana daripada pembakaran dengan ketara akan memberi manfaat kepada industri untuk menggunakan bahan api biodiesel yang lebih bersih, selamat dan mampan untuk penjanaan tenaga mereka.

Kata kunci: Jatropha methyl ester, bahan api diesel konvensional, ciri-ciri, pembakaran, pelepasan.

1.0 INTRODUCTION

The world remains reliant on crude petroleum as the main source of energy production to sustain human activities (Rodríguez Ramos *et al.* 2018), despite the necessity of petroleum and its by-products has been decreasing in recent years (Camp *et al.* 2020). Limited main energy sources, the increase of environmental awareness, and the addition of advanced technology have stimulated the search for alternative sources for petroleum-based fuels, which are more economical, sustainable and viable for substitution. Amongst other possible substitutes, biofuel is seen to be a sustainable alternative to petroleum as it is unbounded by geopolitical instability and environmentally friendly (Rodionova *et al.* 2017; Nordin *et al.* 2022)).

Biodiesel is an example of Biofuel. It is produced from a transesterification process which converts high-viscosity oil to a less viscous fatty acid alkyl ester and usable glycerol with the aid of an acid such as sulphuric acid (H_2SO_4) or hydrochloric acid (HCl and base catalyst such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), as shown in Figure 1. Using ethanol during transesterification produces ethyl ester, which can then be combined with conventional diesel fuel (CDF) at different proportion in a diesel engine or non-transportation applications such as in gas turbine and burner (N. Abdul Rahim 2017; Canakci and Van Gerpen 1999).

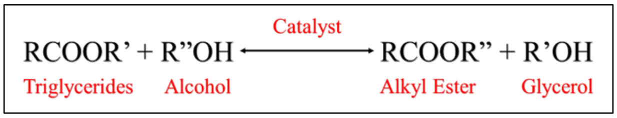


Figure 1 Producing alkyl ester and glycerol from triglycerides and alcohol

Biodiesel can be generated from edible and non-edible oil feedstock. Edible oil is commonly sourced from plants such as soybean, sunflower, rapeseed, oil palm, and coconut. Edible oils yield high-quality oils through transesterification (Mohd Jaafar 2011). With the existence of very large oil palm and coconut plantations in South East Asia and other tropical countries, this type is viable for mass production. Nonetheless, there has been a rivalry for its utilization between the need for fuel production and the demand in food industries. With the high demand of both purposes and restrictions for plantation development in some countries, availability of biodiesel generated from edible oils would fluctuate dramatically. Therefore, it appears that their reliability is more dependent on the policy and market, instead of the producing technology.

Alternatives to edible oils have recently been sought, to name a few: Karanja, Polanga, Castor, Jatropha and others (Atiqah *et al.* 2021; Khan *et al.* 2021). Oils extracted from these plants are generally non-edible; hence, they could specifically be developed for biodiesel. Amongst other feasible sources, Jatropha-Curcas can massively be planted in large scale. Despite its chemical composition affected by climate and locality (Aminul Islam *et al.* 2017; Anggono *et al.* 2022), Jatropha generally suits dry climate or abandoned agricultural lands (Kalam *et al.* 2012; Aghbashlo *et al.* 2021). Gibbs and Salmon (2015) reported that abandoned lands cover around approximately half of a billion hectares only in Asian continent. With this amount, biodiesel development based on non-edible oils could prospectively be established throughout Asia and Africa.

Although potential lands supporting the industry have been identified, survey of the literature suggests that paucity of technologies related to efficient oil extraction from Jatropha plant is evident. This leads to partially resolved issues, requiring more research. Jatropha crude oil contains high Free Fatty Acid (FFA), around 14% to 21.6% (Farouk *et al.* 2020; Taipabu *et al.* 2021) which is beyond the limit of 1% FFA suitable for base catalysed transesterification process. Therefore, acid catalysed transesterification is required to reduce FFA content below 1% before performing base catalysed transesterification (Bohlouli and Mahdavian 2019; Norwazan *et al.* 2018). As reported by Akbar *et al.* (2009) and Dharma *et al.* (2016), Jatropha oil contained higher amount of unsaturated fatty acid than saturated one, about 76.5% to 79%, comprised from oleic and linolenic acid. These features contribute to high cold flow properties of Jatropha biodiesel.

Concern of gas emissions applies to biodiesel developed from either edible or non-edible oils. Emitted gases, especially NO_X and CO which are considerably harmful to humans, from edible oils have long been studied. Ganjehkaviri *et al.* (2016) studied emission concentration of firing Palm Oil Methyl Ester (POME) and found that emission may be affected by changes in nozzle volumetric flow rates. In another study, Abdul Malik *et al.* (2017) utilized Coconut Methyl Ester (COME) based biodiesel. They concluded that increasing COME content in biodiesel blends contributed to least formation of NO_X, CO and SO_2 was observed. In addition, combustion of increased Waste Cooking Oil Methyl Ester (WCOME) biodiesel blends reduced aforementioned gas emission (Mohd Ja'afar *et al.* 2020; Aziz *et al.* 2020). While advances have been made using edible oils, it appears that non-edible oils like Jatropha oils have been understudied, making their applicability to humans and the environment least understood. In particular, the paucity of research related to biodiesel blends is evident in the literature.

The aim of this research is, therefore, to investigate the potentials of Jatropha biodiesel blends as an alternative to biodiesel from edible oils. Specifically, this research compared the performance between conventional diesel fuel (CDF) and biodiesel fuel blends of B5, B15 and B25 from Jatropha oil. Evaluation was made by examining temperature and flame profiles as well as NO_X and CO emission patterns produced during combustion.

2.0 METHODOLOGY

About five litres of JME for production of B5, B15 and B25 biodiesel blends were produced from a two-step acid and base catalysed transesterification process to reduce high FFA content of Crude Jatropha Oil (CJO) before separating JME from glycerol. This process was conducted using conventional laboratory apparatus. Transesterification process involves three stages, which are: pre-treatment, transesterification and post-treatment. Crude jatropha oil from Bionas, Kuala Lumpur was filtered and heated at 60 °C at 400rpm for one hour using a rotary evaporator in a pre-treatment process to remove any impurities and moisture from the feedstock.

In the first stage of transesterification, methanol (MeOH) and sulphuric acid (H_2SO_4) from Merck Malaysia, Shah Alam were used to convert high FFA in CJO to JME. Precisely 50%v/v of MeOH was added into preheated CJO in a round flask and heated in stirring mode to 50 °C, followed by adding 1.5% v/v of H_2SO_4 into the mixture. A reflux condenser with running water was installed at the top of the flask to condense vaporised MeOH back into the mixture. It was let to react for three hours at constant stirring speed and temperature of 400 rpm and 60 °C respectively. After the reaction completed, the mixture was then poured into a separating funnel and was left for two to three hours to separate the JME, CJO and water from hydrate gum, and the excess of MeOH and H_2SO_4. The JME, CJO and water accumulating at the bottom layer were taken out and heated for one hour at a temperature of 90 to 95 °C to remove water content.

Base catalysed transesterification process was then carried out to produce JME from triglycerides of CJO. JME and CJO mixture were filled into a round flask and heated with stirring mode applied at 50 °C. About 1% w/w potassium hydroxide (KOH) from Merck Malaysia, Shah Alam was added to 25%v/v of MeOH before pouring into the mixture. The reaction was conducted for two hours at constant temperature with stirring speed of 60 °C and 400 rpm, respectively. The mixture was subsequently injected into a separated funnel and let to rest overnight to separate JME from glycerol. With this procedure, impurities were formed at the bottom layer of the funnel, requiring their removal before post-treatment process. Figure 2 shows separation of JME (upper layer) from glycerol and impurities (bottom layer) during CJO transesterification.

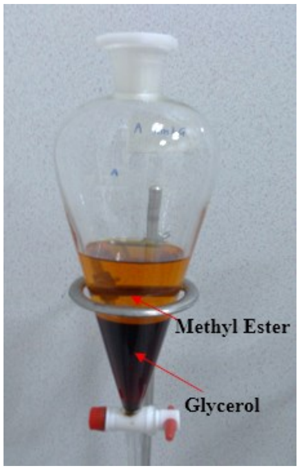


Figure 2 The base catalysed transesterification process of CJO to obtain JME

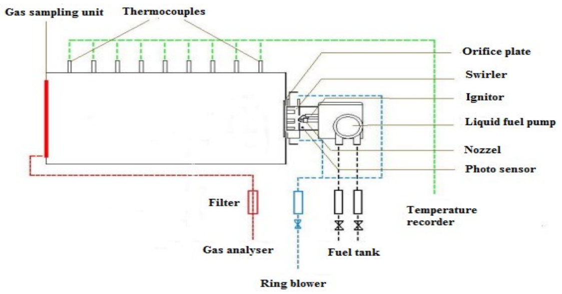
During post-treatment process, JME was washed using pre-heated (between 50 °C to 60 °C) distilled water to remove excess KOH and MeOH. About 50% (v/v) of distilled water was poured into a separation funnel and shaken to allow proper mixing. The process was done several times until the pH of the washing water was close to neutral (pH=7). Later, JME was heated using a rotary evaporator at temperature of 100 °C for 30 minutes to remove any remaining water. After the process was completed, purified JME was filtered to remove residual impurities before the preparation of JME biodiesel blends.

Table 1 Fuel properties of CDF, JME B5, B15, B25 and B100

Properties	Standard method	Fuels				
		Jatropha Methyl Ester (JME)				
		CDF	B5	B15	B25	B100
% JME Volume (L)	-	0	0.5	1.5	2.5	-
% CDF Volume (L)	-	100	9.5	8.5	7.5	-
Density (kg/m³)	ASTM D941	830.1	833.8	837.4	841.0	868
Kinematic Viscosity 40 °C (mm²/s)	ASTM D445	3.5018	3.5802	3.6795	3.711	4.4761
Surface Tension (mN/m)	ASTM D971	29.5	29.7	29.9	30.1	31.6
Calorific Value (kJ/kg)	ASTM D240	45,290	44,832	44,209	43,586	39,517

A 20 Litre fuel mixer was used to produce 10 Litre JME blends of B5, B15 and B25. Blending was done for several hours until the fuel specific gravity (SG) achieved a constant, homogeneous reading. Fuel properties of pure JME (B100), CDF and their blends were then examined and identified. Table 1 depicts the properties of CDF, JME B5, JME B15, JME B25 and JME B100.

CDF and JME biodiesel blends were ignited and fired inside an open-ended combustion chamber using Baltur BTL-10 industrial grade light oil burner fixed with a 1.5 Gal/hr Steinen solid cone spray producing a fine atomized fuel pattern at an angle of 45°. The 1000 mm length and 400 mm diameter combustion chamber was equipped with two concentric cylinders of 2 mm thickness, made of mild steel, filled with 100 mm thick fireproof (Hycast) cement as an insulation capable of handling temperatures ranging from 1200 to 1600 °C. Eight type-K thermocouples were placed along the top of the chamber with a uniform separation of 100mm. These thermocouples were connected to a Midi temperature sensor to display and record the wall temperature within ±1.0 °C tolerance. A Horiba Enda 5000 sampling gas analyser unit was placed in front of combustion chamber to measure exhaust NO_X and CO emissions within ±1 ppm tolerance. Figure 3 (a) illustrates a schematic diagram of the burner test rig while Figure 3 (b) shows the combustion experiment test.



(a)

(b)

Figure 3 (a) The design of burner test rig; (b) combustion trial

All fuels were combusted from Equivalence Ratio of 0.8 to 1.2 to simulate three different combustion conditions as defined by the Equivalence Ratio, Φ, in Equation 1. Lean fuel combustion burns all the fuel in an excess air supply condition, while rich fuel burned in a reduced supply of air. A balanced quantity between fuel and air is considered as stoichiometry.

$$\text{Equivalent Ratio, } \Phi = \frac{\left({}^{m_{Fuel}}/{}_{m_{Air}}\right)_{Actual}}{\left({}^{m_{Fuel}}/{}_{m_{Air}}\right)_{Stoichiometry}}, \qquad (1)$$

Stoichiometry → $\Phi = 1$,
Lean Fuel → $\Phi < 1$, and
Rich Fuel → $\Phi > 1$

For every Φ, combustion process for each fuel was conducted several times prior averaging the wall temperature and concentrations of NO_X and CO. Average temperatures were plotted against thermocouple distance away from the burner throat, while average NO_X and CO were charted against Φ for all the tested fuels.

3.0 RESULTS AND DISCUSSION

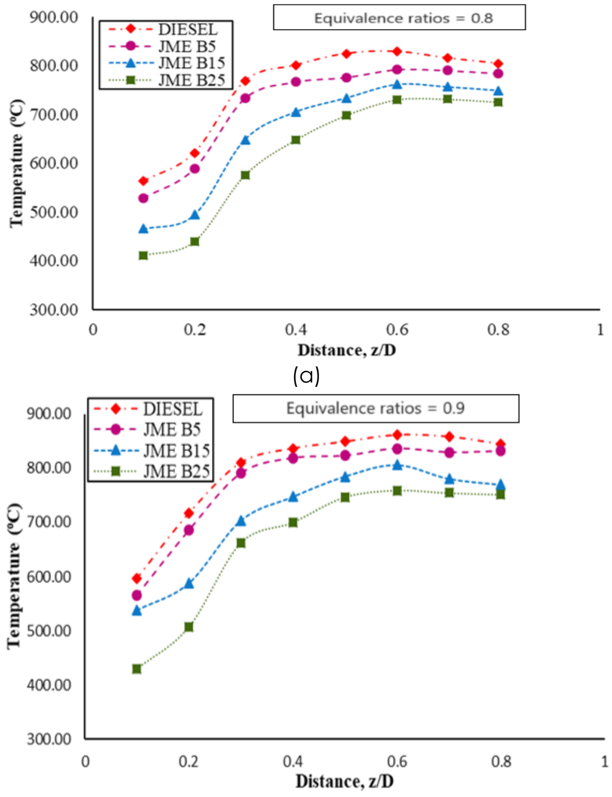
The results and discussion of this study are focused on the wall temperature profiles of the combustion chamber and emission formation of NO_X and CO for each biodiesel blend B5, B15 and B25 at a determined equivalence ratio of 0.8, 0.9, 1.0, 1.1 and 1.2 by comparing them to diesel fuels (CDF). The temperature readings are plotted against z/D, which is the ratio of thermocouple distance, z, to the diameter of the combustion chamber, D. The emission concentrations of NO_X and CO are plotted against the equivalence ratios for all the tested fuels.

3.1 Wall Temperature Profile

Figure 4 depicts the comparison of wall temperature profiles between CDF and JME biodiesel blends with equivalence ratio ranging from 0.8 to 1.2. Result shows that temperature profile for all fuels increases until reaching the peak point at z/D=0.6. At this peak, temperature was at a maximum level for every fuel type due to high heat intensity released from combustion of homogeneous mixture of air and fuel. Beyond this point, the system experienced reduction in temperature up to the end of the chamber. It was observed that shifting all fuels combustion, from lean fuel to stoichiometry and rich fuel, increased wall temperature profile. The highest profile was achieved at Φ=1.2, when all fuels were excessively burned in lowest air supply. By referring to the finding from Ganjehkaviri *et al.* (2016), one could indicate that the increase of fuel supply during combustion will result in a greater heat released during combustion, thus increasing wall temperature.

The highest temperature profile was formed by CDF followed by JME biodiesel of B5, B15 and B25. At stoichiometric condition, CDF generated the highest maximum wall temperature of 900.0 °C, followed by B5 at 850 °C, B15 at 840.3 °C, and B25 at 820 °C. The reduction in wall temperature for JME B5 to CDF is 5.56%, followed by B15 at 6.63% and B25 at 8.89%. As JME percentage for biodiesel increases from B5 to B25, the temperature profile and maximum wall temperature reduced significantly. The temperature reduction observed between JME and its blends (B5, B15 and B25) is caused by the decrease in calorific value, as presented in Table 1.

Another factor which influenced the temperature decline is the kinematic viscosity of fuel blends. The kinematic viscosity accounts for the smoothness of the fuel flow during combustion. Blends that have higher kinematic viscosity has a lower degree of atomization and creates higher carbon content. CDF is seen to have a lower kinematic viscosity of 3.5018 mm^2/s compared to JME blends B5, B15 and B25 of 3.5802 mm^2/s, 3.6795 mm^2/s and 3.711 mm^2/s respectively. Lower kinematic viscosity allows the nozzle to atomize the fuel into small *ds*. Besides kinematic viscosity, the temperature decline is also caused by the surface tension of the fuels. JME fuel blends are found to have higher surface tension compared to CDF. Similarly, the surface tension also affects the atomization process, whereby higher surface tension creates larger droplets. This experiment further concludes that an increase in JME composition in fuel blends affects the fuels' ability to atomize – such that the temperature and calorific value is reduced. This is consistent with the studies conducted by previous researchers (Abdul Malik *et al.* 2017; Norwazan Abdul Rahim *et al.* 2016; Ganjehkaviri *et al.* 2016; Mohd Ja'afar *et al.* 2020).



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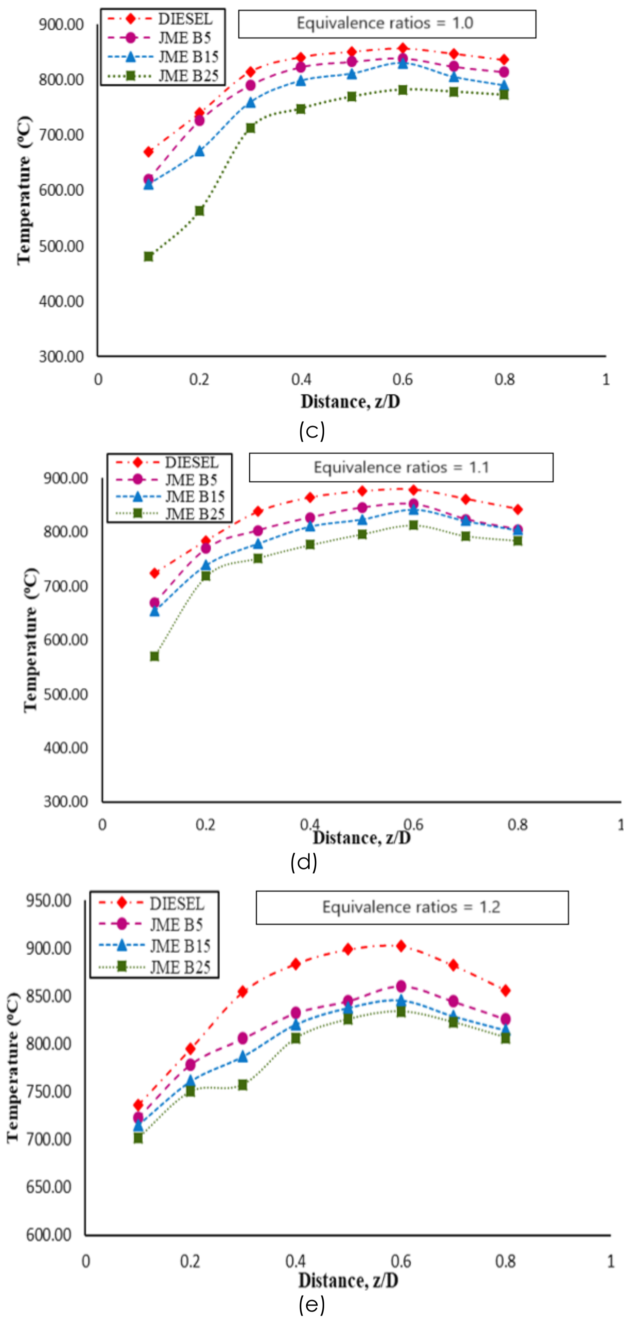

(c)

(d)

(e)

Figure 4 Wall temperature for different equivalence ratios (a) 0.8, (b) 0.9, (c) 1.0, (d) 1.1 and (e) 1.2

3.2 Gaseous Emissions

Formation of pollutant emissions, especially CO and NO$_X$, at higher concentration inflicts a negative impact to the environment and human health. As fuel combustion may serve as an anthropogenic contributor to pollution, it is imperative to obtain the emission level during utilization of JME biodiesel blends. This is to ensure its potential to reduce fossil fuel dependency in energy-related industrial operations.

3.2.1 NO$_X$ Emission

Figure 5 shows NO$_X$ measurements across Φ for CDF and JME biodiesel blends. The pattern of NO$_X$ formation shared similar pattern to a bell-shaped curve, where formation of NO$_X$ started to increase during lean fuel towards stoichiometry combustion. Throughout the combustion, the presence of excess oxygen allowed the amplifications of combustion temperature and oxidation of oxygen and nitrogen to form NO. Thermal effects continue to increase NO until it reached stoichiometric conditions, which contributed to the increasing NO$_X$ formation (Seela *et al.* 2017). NO$_X$ formation for all fuels was seen to reach its peak during stoichiometry. This was due to the fact that stoichiometric combustion releases its highest heat point during the reaction, thus increasing the temperature of the process and enhancing the formation of NO$_X$ (Karki *et al.* 2017; Mohd Ja'afar 2014). As the combustion entered a rich fuel condition, the formation of NO$_X$ decreased as a result of low concentration of air due to the restricted reaction between nitrogen and oxygen to produce NO (Abdul Malik *et al.* 2017). Similar findings were observed in previous research (Bhavani Shankar and Khandelwal 2013; Kroyan *et al.* 2022) suggesting that NO emissions could be suppressed through managing the equivalence ratio.

The highest NO$_X$ concentration was formed by CDF followed by JME biodiesel blends of B5, B15 and the lowest by B25, suggesting that application of higher concentration of Jatropha oil could reduce NOx emission. At stoichiometry, CDF emits 60.00 ppm of NO$_X$, followed by JME B5 at 58.00 ppm, JME B15 at 52.00 ppm and JME B25 at 47.00 ppm. It can be observed from Figure 5 that increasing the JME content in biodiesel blend contributed to the reduction of NO$_X$ formation. At stoichiometry, the reduction of NO$_X$ as a result of implementing Jatropha oil with blend concentration B5, B15 and B25 was fairly significant, i.e. 3.33%, 16.67% and 21.67% respectively. This can be explained by the presence of excess oxygen in biodiesel which requires less air (which consist about 80% nitrogen) to fully combust the fuel (Kroyan *et al.* 2022). In addition, biodiesel from fatty acid methyl ester discounts aromatic content; hence, contributing to a lesser amount of released NO$_X$ (Bhavani Shankar and Khandelwal 2013). The outcome of this research is in agreement with a study by Bravo *et al.* (2022), concluding that NO$_X$ emission was depleted as a result of biofuel addition, with a strong reduction for B100 blend.

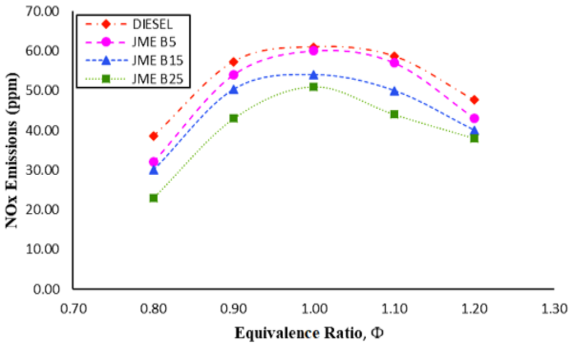

Figure 5 NO_X emissions profile for diesel and different JME biodiesel blends

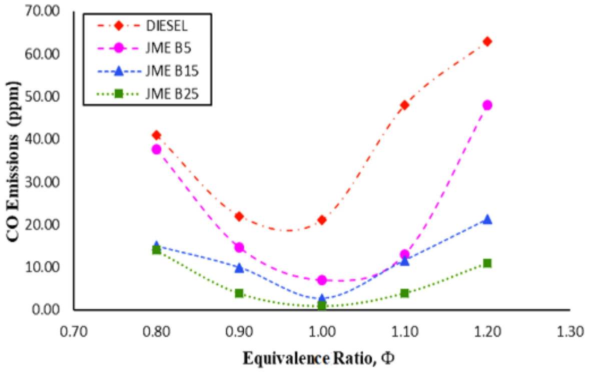

Figure 6 CO emissions profile for diesel and different JME biodiesel blends

3.2.2 CO Emission

Figure 6 depicts the average formation of CO emissions from firing CDF and JME biodiesel blends across all equivalent ratios. The figure indicates that CO formation for fuel-lean combustion continue to decrease until it reached the lowest rate at stoichiometric, then increase again when the combustion transits to the rich fuel region. The finding of this research correlates to the study conducted by Lefebvre (1998) and Escott (1993).

Formation of CO for all fuels are influenced by two factors, i.e. the oxygen (O_2) supply during combustion and the temperature of fuel combustion (Dubey and Gupta 2017). During lean combustion, oxygen is abundant and the combustion temperature is high enough to combust, forming low concentrations of CO. As the combustion shifts to stoichiometry, increasing temperature helps to oxidize a majority of CO into CO_2, resulting in a very low formation of CO emissions. However, as the combustion enters the rich fuel region, CO formation for all fuels begin to rise due to the lack of oxygen and reduction in temperature which promotes incomplete fuel combustion, thus enhancing partial oxidation of carbon compound to CO. It was observed that CDF produced the highest CO amount followed by JME biodiesel blends of B5, B15 and B25. Firing CDF at stoichiometry combustion generated 20 ppm CO emission, followed by JME B5, B15 and B25 at 10 ppm, 5 ppm and 4 ppm, respectively. This corresponds to a 50%, 75% and 80% reduction in CO formation for the JME B5, B15 and B25 when compared to CDF. This research clearly suggest that increasing the JME content in biodiesel significantly reduces CO formation across all equivalent ratios. This can be explained by the amount of oxygen content inside biodiesel, which is usually between 10 and 12 percent higher than CDF, hence promoting complete combustion by enhancing the oxidation of CO into CO_2. Apart from that, extra oxygen content in biodiesel shortens fuel ignition delay which helped reduce CO formation during combustion (Abdullah *et al.* 2015).

3.2.3 Flame Profile

Another important aspect during combustion is the formation of the flame profile, where a good flame profile indicates perfect condition mixing of fuel and air. Flame profile also designates the behaviour of the flame with respect to the equivalent ratio (Dubey and Gupta 2017) in which increasing equivalence ratios can yield shorter flames, higher temperature along with reduction of emission formations. Additionally, the rate of soot formation determines the rate of emissions generated during combustion process. According to Mestre (1974), a yellow, long distance flame indicates the combustion of fuel and air was incomplete, suggesting the intensification of CO and UHC formation. Lefebvre (1998) further added that emission problem could be resolved by producing a short flame. Combustion will thus occur faster due to the shorter flame length, leading to larger flame diameter due to a larger circulation zone. (Morcos and Abdel-Rahim 1999).

Figure 7 displays the formation of the flame profile at the equivalence ratio of 1.2 for diesel fuel compared with biodiesel blends of B5, B15 and B25. Based on these flame profiles, flame length at equivalence ratio of 1.2 is the shortest. This flame possessed the highest temperature readings at about 900 °C for diesel, as shown in Figure 4. This equivalence ratio generated low NO_X emissions (Figure 5) and CO (Figure 6), especially for biodiesel blend B25. Thus, the lowest emission of NO_X and CO value in this study, based on equivalence value, was achieved by biodiesel blend B25. This suggests that B25 was better than conventional diesel fuel in the formation of emissions.

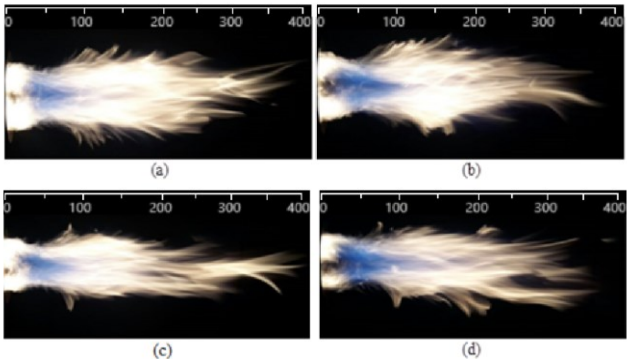

Figure 7 Flame profile at equivalence ratio of 1.2 (a) CDF, (b) B5, (c) B15 and (d) B25

4.0 CONCLUSION

The firing of CDF and JME biodiesel blends of B5, B15 and B25 in a liquid fuel burner system was conducted to investigate the combustor wall temperature profiles and NO_X and CO concentrations, from lean fuel combustion (Φ=0.8) to rich fuel (Φ=1.2). Physical properties for JME biodiesel blends in term of density, kinematic viscosity, surface tension, and calorific value were determined, with CDF as the benchmark. CDF was found to have the highest calorific value compared to other fuel blends. In contrast, all fuel blends (B5, B15 and B25) were found to have lower calorific value with higher kinematic viscosity, density and surface tension compared to CDF. These factors affect the combustion process – such that it generates a lower combustion temperature. The result also shows that increasing JME biodiesel blend from B5 to B25 at equivalence ratio of 1.2 generated a significant reduction of NO_X and CO. Physical characteristics of JME biodiesel blends were found to have a minimum dissimilarity to the benchmark. This suggests that JME biodiesel could serve as an alternative fuel and therefore, reducing industrial dependency on petroleum, while promoting sustainable environment through the reduction of gaseous emissions.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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