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Article

Performance Evaluation of Palm Oil-Based Biodiesel Combustion in an Oil Burner

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Abstract: This paper presents an experimental investigation of the combustion characteristics of palm methyl ester (PME), also known as palm oil-based biodiesel, in an oil burner system. The performance of conventional diesel fuel (CDF) and various percentages of diesel blended with palm oil-based biodiesel is also studied to evaluate their performance. The performance of the various fuels is evaluated based on the temperature profile of the combustor's wall and emissions, such as nitrogen oxides (NO_x) and carbon monoxide (CO). The combustion experiments were conducted using three different oil burner nozzles (1.25, 1.50 and 1.75 USgal/h) under lean (equivalence ratio (Φ) = 0.8), stoichiometric (Φ = 1) and rich fuel (Φ = 1.2) ratio conditions. The results show that the rate of emission formation decreases as the volume percent of palm biodiesel in a blend increases. PME combustion tests present a lower temperature inside the chamber compared to CDF combustion. High rates of NO_x formation occur under lean mixture conditions with the presence of high nitrogen and sufficient temperature, whereas high CO occurs for rich mixtures with low oxygen presence.

Keywords: palm oil; combustion; NO_x; oil burner; equivalence ratio

1. Introduction

In recent years, global interest in biodiesel production and utilization has increased significantly due to the international energy crisis, global warming and climate change, as well as fossil fuel depletion [1]. Biodiesels, which are fatty acid methyl or ethyl esters made from biomass vegetable oils, are non-polluting fuels and a renewable energy source. Biodiesels are recognized as a viable substitutes for diesel fuel which can be produced with similar functional properties as fossil fuels from local feedstocks. A variety of feedstocks can be employed for biodiesel production like rapeseed, soybean, palm oil and jatropha [2]. Palm oil, as one of the main agricultural products in Malaysia, is mostly applied for biodiesel production in that region. Palm oil-based biofuel could generate a similar efficiency as diesel fuel with lower pollutant emissions, but with higher specific fuel consumption. Moreover, palm oil-based biofuel can be applied in compression ignition (diesel) engines without significant modifications. It also can be blended at any percentage level with petroleum diesel to create biodiesel blends [3]. Biodiesel can be produced from palm oil through a transesterification process, in which the triglycerides (free fatty acid and water contents) from palm oil react with an alcohol (ethanol or methanol) to form ethyl or methyl esters (biodiesel) and glycerol. The fleshy inner wall of the palm fruit called mesocarp is processed to obtain the palm oil. The step by step process of crude palm oil (CPO) and finally palm oil-based biodiesel production is illustrated in Figure 1. CPO is produced from the mesocarp through refining and kernel processing. Approximately 25%–28% of CPO can be produced from a palm bunch. CPO is processed into refined palm oil which can then be used for multiple applications, including palm oil biodiesel production. Palm oil is processed into CPO, then into refined oil before being processed into palm oil biodiesel. Palm oil biodiesel can be either be processed into an ester or blended in certain proportions with petroleum diesel [4].

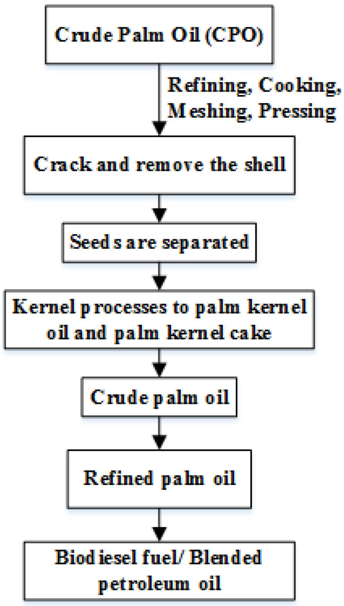


Figure 1. The process of palm oil-based biodiesel production.

Today, the increasing rate of exhaust emissions, which cause increases in the greenhouse effect, global warming, weakening of the ozone layer, acid rains, *etc*. has become another major problem in the utilization of fossil fuels. These negative air pollution effects are affecting the health of the world's population by damaging the respiratory system, and causing nervous breakdowns and skin diseases. For these reasons, biodiesel fuel was reported by many researchers as the best substitute for fossil fuels to produce lower emissions [5]. Lapuerta *et al*. [6] reported that lower emissions of soot, carbon monoxide (CO) and carbon dioxide (CO_2), but higher nitrogen oxides (NO_x), were achieved by using biodiesel in a diesel engine. Szybist *et al*. [7] pointed out that compared to conventional diesel fuel (CDF) at high load, biodiesel blends generate 6%–9% higher NO_x emissions. For gas turbine engines, Sequera *et al*. [8] investigated the emissions of diesel and biodiesel using swirl burner gas turbine engines. Their results illustrated that biodiesel blended fuels emitted lower NO_x and CO at constant fuel flow rates. It was reported that palm oil biodiesel blends have the potential to reduce harmful emissions from the burner system [9]. Mantari and Jaafar *et al*. [10] studied the combustion performance of an oil burner by utilizing Refined, Bleached and Deodorized Palm Oil (RBDPO) biofuel blends. Their results indicated the biofuel blends decreased NO_x and CO emissions. Several parameters such as physicochemical properties and molecular structure of biodiesel, adiabatic flame temperature, ignition delay time, injection timing and engine load conditions impact the rate of NO_x formation in biodiesel combustion [11]. Mofijur *et al*. [12] compared the combustion characteristics of biodiesel obtained from a non-edible oil source (*Moringa oleifera*) with palm oil-based biodiesel and diesel fuel. The performance of these fuels was evaluated in a multi-cylinder diesel engine at different engine speeds and under full-load conditions whereas emissions were studied under both full-load and half load conditions. It was stipulated that since palm oil-based biodiesel generates lower exhaust emissions than diesel fuel, these fuels can replace diesel fuel in unmodified engines to decrease the global energy demand and exhaust emissions to the environment. Although, numerous studies about biodiesel utilization in diesel engines have been reported, a few biodiesel combustion tests in oil burner systems has been reported. In this paper, the combustion performance of palm oil-based biodiesel is investigated using an oil burner system. The results such as temperature variation inside the chamber and exhaust emissions are obtained under various operating conditions, including different nozzle burners and various air fuel ratios. The performance and emissions of the palm oil-based biodiesel in comparison with CDF are also investigated.

2. Experimental Setup

The fuels used in the experiment is CDF obtained from a PETRONAS petrol station and palm methyl ester (PME) supplied by Carotino Sdn. Bhd., Johor Bahru, Malaysia. Blends of palm biodiesel with diesel fuel were also used in these experiments. The percentage volume of palm biodiesel in the employed blends is given in Table 1. The palm oil-based biodiesel blends were prepared using a lab scale mixer by direct blending of PME with CDF. The properties of all types of fuels were examined in the lab and conformed to the standard fuel specifications. The PME conforms to the European Standard for Biodiesel (EN 14214) and CDF conforms the European Automotive Diesel Standard (EN 590) [13,14]. The uncertainties for each piece of equipment used to examine the fuel properties are about ±5%. The properties of CDF, PME and its blends (B10, B20 and B40) are also shown in Table 1.

Table 1. Properties of conventional diesel fuel (CDF), palm biodiesel blends and palm methyl ester (PME).

Properties	Fuels				
	CDF	**B10**	**B20**	**B40**	**PME**
% PME Volume	0	10	20	40	100
% CDF Volume	100	90	80	60	0
Density (kg/m^3)	835.91	837.85	841.72	848.49	864.94
Kinematic Viscosity 40 °C (mm^2/s)	3.0625	3.8379	3.9180	4.1510	4.5696
Surface Tension (mN/m)	29.57	29.83	30.17	30.60	32.03
Calorific Value (kJ/kg)	45,632	45,120	44,609	43,474	40,521

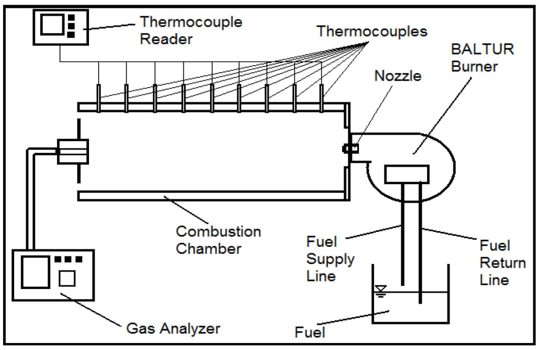
The oil burner test rig used in the experiment consists of open ended combustion chamber with mild steel of 2 mm thickness forming the combustor wall. Hy-cast cement is used as insulation for the combustion chamber. The outer and inner diameter of chamber are 400 and 300 mm respectively and the length of the chamber is 1000 mm. Nine hole openings in the combustion chamber were used to install the thermocouples. The type of burner used in this experiment is an axial swirl burner. The specifications of the burner are shown in Table 2.

Table 2. Burner specifications (Baltur IL BT 14 G/W Light Oil Burner).

Capacity	Fuel	Voltage	Power Output	Thermic Capacity
7.5–14.5 kg/h	1.5 °E/20 °C	230 V	140 kW	89–172 kW

The experimental setup for the oil burner is shown in Figure 2. The burner and combustion chamber are placed horizontally on a fixed structure. Air is supplied by a compressor in the BULTUR burner. For all tests, a gas analyzer tube is mounted at the end of chamber. This gas analyzer is used to measure the exhaust emissions produced during the combustion tests. The thermocouples employed are K-type which are attached to a thermocouple reader. Tests were carried out at ambient temperature for the inlet air and no preheating devices were used in these tests. Combustion air was supplied from the main air compressor in the laboratory. The air supply pressure was metered using an air pressure regulator.

The experiments have been conducted using a solid atomizer oil burner with three different nozzles (1.25, 1.50 and 1.75 USgal/h) that provide different volumetric fuel flow rates as presented in Table 3.



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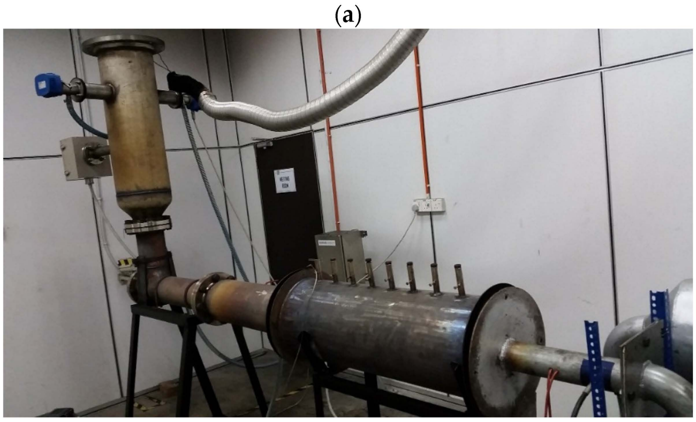

(**b**)

Figure 2. (**a**) Schematic diagram of burner test rig setup; (**b**) Combustion chamber photo.

Table 3. Nozzle flow rates.

Type	Volume Flow Rate		Spray Angle (º)
	USgal/h	m^3/h	
Nozzle 1.25	1.25	0.004731765	45
Nozzle 1.50	1.50	0.005678118	45
Nozzle 1.75	1.75	0.006624471	45

Figure 3 illustrates the various nozzles employed for the combustion tests. These nozzles are a solid cone type with a 45° spray angle. This type of atomizer is used because it is able to produce a uniform spray distribution pattern and is used in the oil burner industry [15].

Figure 3. Solid atomizer type nozzles with 45° spray angles.

The tests were done at three different equivalence ratios (0.8, 1.0 and 1.2) for each nozzle. The air and fuel mass flow rates are metered accordingly based on the nozzle flow rates and fuel's energy content which from the calorific value for each fuel is calculated.

3. Results and Discussion

3.1. Wall Temperature of the Chamber

The wall temperature was measured using thermocouples (K-type) placed at nine points along the combustion chamber starting from the burner outlet until the end of the chamber (the distance between each point is 100 mm). Experimental results confirm that diesel fuel generated higher wall temperatures than palm oil-based biodiesel and its blends during the combustion tests. Under stoichiometric conditions, the combustion of CDF produced a maximum wall temperature value of 704.6 °C (with the 1.25 nozzle), 723 °C (1.50 nozzle) and 763.9 °C (1.75 nozzle), whereas, PME produced a maximum wall temperature value of 620 °C (1.25 nozzle), 641.1 °C (1.50 nozzle) and 681.3 °C (1.75 nozzle). These peak temperatures occur at the middle distance of the combustor due to the high heat intensity at that point.

The combustor wall temperature trends of the 1.25, 1.50 and 1.75 nozzles are illustrated in Figures 4–6 respectively. From these figures it can be seen that the wall temperature decreases when the percentage volume of palm oil-based biodiesel increases (CDF has a high calorific value and the energy content of CDF is much higher than that of PME). The variations of wall temperature profile for biodiesel blends (B10 and B20) are very low though their temperature is near diesel's temperature because their properties have insignificant differences with diesel fuel. PME has the lowest wall temperature profile because compared to the other blends of palm oil-based biodiesel, PME has the lowest energy content while its high viscosity and surface tension can cause poor atomization during combustion.

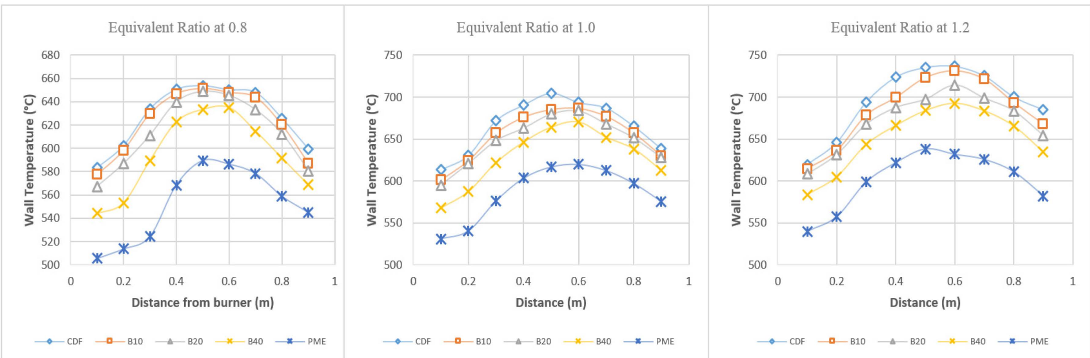

Figure 4. Wall temperature profiles for the 1.25 nozzle.

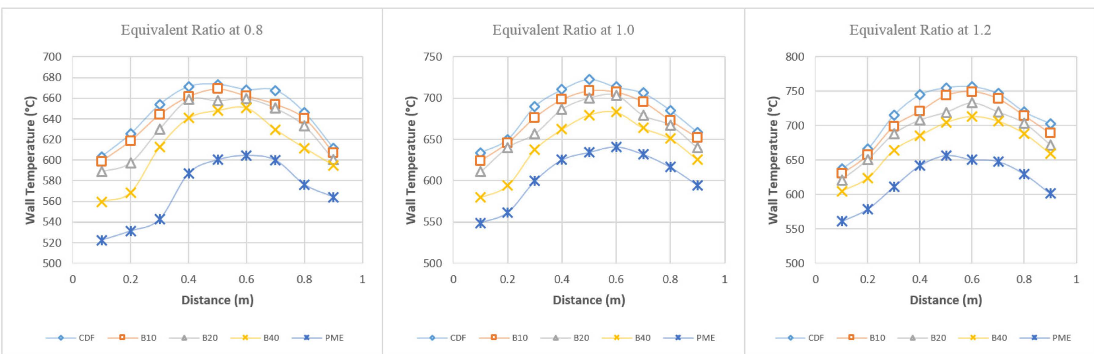

Figure 5. Wall temperature profiles for the 1.50 nozzle.

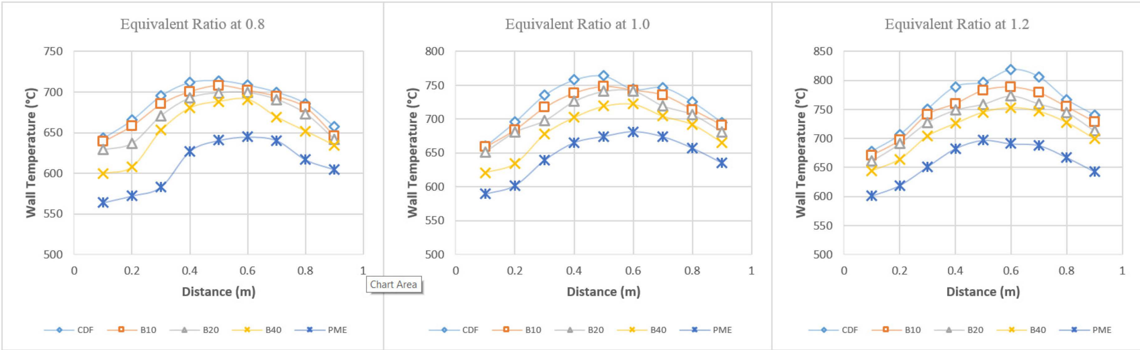

Figure 6. Wall temperature profiles for the 1.75 nozzle.

The influence of the equivalence ratio (defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio) on the wall temperature profile of the combustor shows that the average wall temperature in PME combustion at equivalence ratios of 1.0 and 1.2 increases about 6% and 9%, respectively, compared to the equivalence ratio of 0.8 for the 1.25 nozzle. This means a higher equivalence ratio produces a higher wall temperature profile in all kinds of tested fuel because more fuel is burned at the higher equivalence ratio and consequently more heat is released during combustion. However, rich mixtures cause incomplete combustion because they burn without enough air. In an experiment done by [16] it was stipulated that the temperature increases slowly with the increase of equivalence ratio for biodiesel fuels.

To investigate the correlation between fuel flow rate and the performance of the combustion system, experiments were done using different burner nozzles which have different volumetric fuel flow rates (1.25, 1.50 and 1.75 USgal/h). Besides, according to [17], fuel flow rate can be used to calculate the estimated emissions in order to follow the regulatory requirements in industrial combustion apart from combustor design purposes. The wall temperature profile for each nozzle was also measured as presented in Figures 4–6. For an equivalence ratio of 1, the combustion of PME using the 1.25 nozzle produced the maximum wall temperature (620 °C) at point 6. By using 1.50 and 1.75 nozzles, the maximum wall temperatures appeared at point 6 with 641.1 and 681.1 °C, respectively. Compared to the 1.25 nozzle, the wall temperature of the combustor increases 3% and 10% with the 1.50 and 1.75 nozzles, respectively, which indicates that a higher volumetric flow rate of PME was used in the combustion. Utilization of a higher volumetric fuel flow rate in the combustion tests makes more fuel be burnt and consequently more energy content in the fuel released and leads to an increased temperature inside the system chamber.

The similarity that can be observed from the graph confirms that the wall temperature profile pattern is the same for all fuels. From the graph, it can be seen that the temperature increases from the inlet of the combustion chamber (100 mm) until it reaches a distance of 500 mm. The temperature then begins to decrease from the distance of 500 mm until the end of the combustion chamber (900 mm). In fact, the highest temperature inside the combustion chamber was recorded at the distance of 500 mm from the furnace inlet.

3.2. Emissions

One of the key items behind the biodiesel spread strategy is the increasing rate of greenhouse gas emissions and climate change. It is important to know if the emissions from palm oil-based biodiesel blend combustion can reduce the greenhouse gases or not, in order to replace the fossil diesel fuel. CO_2, CO, sulphur oxides, particulate matter, oxides of nitrogen and smoke are the main pollutants which could be formed in palm oil-based biodiesel combustion. In this experiment, gas emissions were measured at the exit of the combustion chamber by mounting the chamber onto an automatic gas analyzer.

3.3. NO_x Formation

The rate of nitrogen oxide (NO_x) formation in biodiesel combustion has become a controversial topic. NO_x formation increases in a combustion process as the excess air and the temperature increase. Some reports indicate that NO_x formation in biodiesel combustion is reduced compared to diesel combustion [18]. However, a rise in NO_x formation in biodiesel combustion [17] as well as similarity of NO_x formation in biodiesel and diesel combustion [19] have been reported too. These various results are due to the different experimental setups used, different biodiesel content, engine type and operating systems. Figure 7 depicts the emission rate of NO_x for each fuel tested at different equivalence ratios and different volumetric fuel flow rates.

From the graph, PME generated the lowest NO_x emission rate of 40 ppm under stoichiometric circumstances with the 1.25 nozzle. Under the same conditions, CDF generated NO_x at a rate of 55 ppm. That represents about a 27.3% reduction in NO_x formation by palm oil-based biodiesel compared to diesel fuel. The abatement of NO_x constitution in PME combustion can be attributed to the lower mean temperature inside the chamber in PME combustion compared with CDF combustion. Moderate temperatures inside the chamber can restrict the reactions of nitrogen with oxygen that require high temperatures to form NO_x. Indeed, it can be stated that PME generates lower NO_x emissions due to its high viscosity. The enhancement of viscosity causes an increase in the length of molecules, consequently nitrogen molecule are suppressed from reacting with oxygen molecules present in biodiesel, resulting in less NO_x formation. The highest NO_x emission recorded with CDF is a rate of 79 ppm with the 1.75 nozzle and an equivalence ratio equal to 0.8. From the results, lean mixtures produced higher NO_x than rich mixtures because more combustion air is supplied and the nitrogen atoms react with oxygen to become NO_x at high temperature. NO_x formation increases when the volumetric fuel flow rates increase due to the higher consumption of fuel and air in the combustion. In stoichiometric combustion of PME using a 1.25 nozzle, NO_x was recorded 40 ppm where under the same conditions with a 1.75 nozzle NO_x it is about 60 ppm. This evidence indicates that the rate of NO_x formation increases about 50% in PME combustion when the fuel flow rate increases.

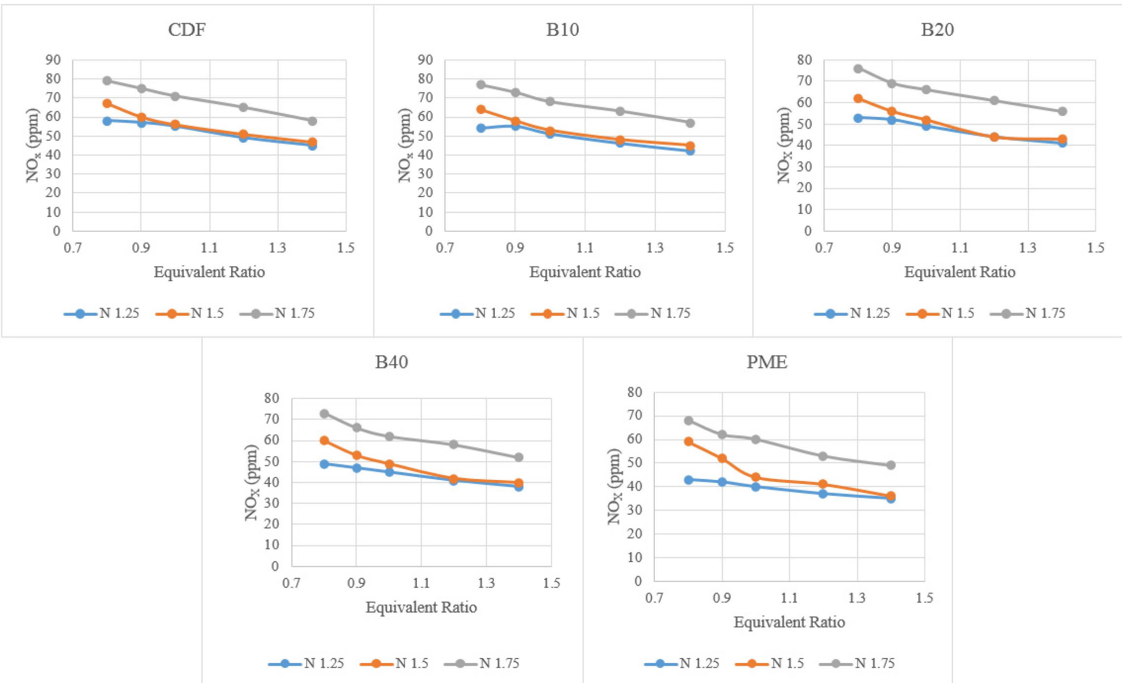

Figure 7. NO_x emissions at various equivalence ratios.

3.4. CO Emissions

Based on the previous reports, it was expected that the rate of CO formation would be lower in biodiesel combustion due to the higher oxygen and lower rate of carbon to hydrogen in biodiesel compared to diesel [20]. Figure 8 displays the CO emissions for each tested fuel at different equivalence ratios and different volumetric fuel flow rates. There was about 8%, 11%, 23% and 30% reduction in CO emissions for B10, B20, B40 and PME, respectively, compared to CDF under stoichiometric circumstanced and a volume fuel flow rate of 1.25 USgal/h.

These results indicate that CO emissions are reduced as the content of biodiesel in blends is raised. The CO emission concentration increases with the increase in the equivalence ratio because rich mixtures have more excess fuel than air and a lack of oxygen for combustion forms high CO concentrations. CO results from the incomplete combustion of carbon fuels during the combustion process, which occurs when enough oxygen is not available. Hence, the CO concentrations are generated from inadequate oxygen supply during the combustion process. The lowest CO formation was recorded at an equivalence ratio equal to 0.8 and the highest is at 1.4. The CO emission pattern during application of different volumetric fuel flow rates are the same but differ in value. By using a nozzle with a volumetric flow rate of 1.25 in the combustion test, B10 fuel produced 1388 ppm of CO emissions at an equivalence ratio of 1.2, but by using a nozzle with a volumetric flow rate of 1.50, B10 fuel produced 1800 ppm of CO emissions at the same equivalence ratio. This indicates that a enhancement of fuel flow rate increases the rate of CO formation in the combustion tests.

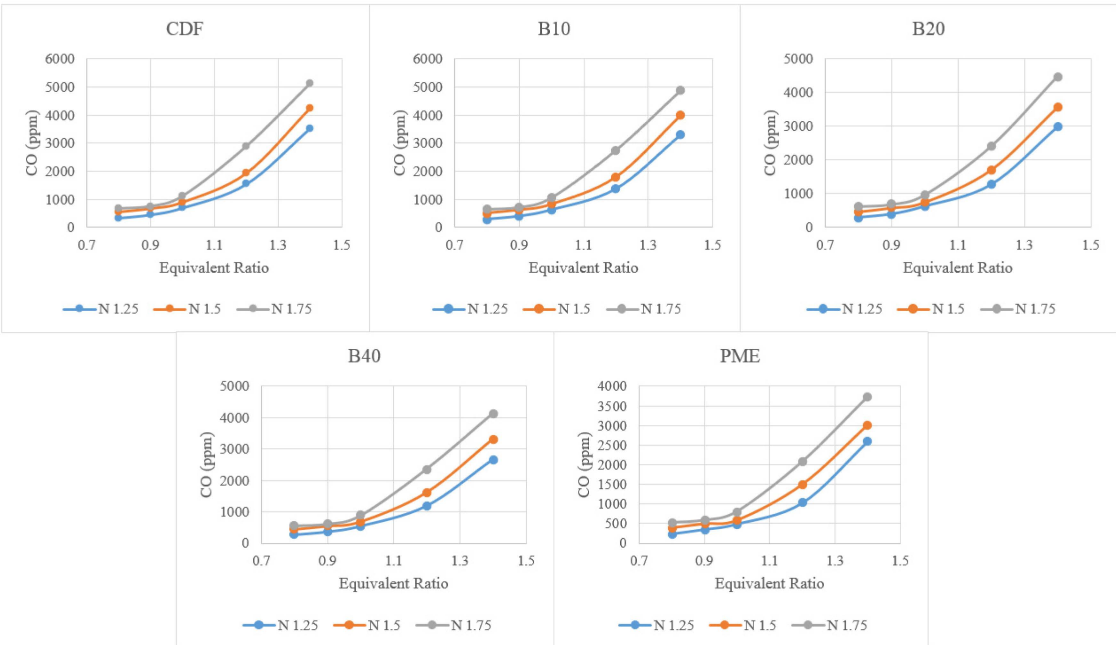

Figure 8. CO emissions at various equivalence ratios.

4. Conclusions

Combustion experiments were conducted using PME, CDF and blends of PME with CDF (B10, B20 and B40). The combustion performance of PME was compared to diesel under various conditions. From the results, it was found that the density, viscosity and surface tension of fuels increased as the percentage of palm biodiesel in the blends increased, while the calorific value of the fuels decreased as the percentage of palm biodiesel in blends increased. The inside temperature of the chamber was reduced when palm oil-based biodiesel content increased in the fuel blends. This means palm oil-based biodiesel combustion generates lower temperatures inside the chamber compared to diesel fuel. Besides, the enhancement of volumetric fuel flow rate raises the combustion temperature. Palm oil-based biodiesel showed lower gas emissiona (NO_x and CO) compared to diesel fuel. Increasing the volumetric fuel flow rate in the combustion generates higher rates of gas emissions. High NO_x formation occurs for lean mixtures with high nitrogen presence and sufficient temperature, whereas high CO occurs in rich mixtures with low oxygen presence.

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Conflicts of Interest: The authors declare no conflict of interest.

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