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RESEARCH ARTICLE OPEN ACCESS

Effects of Non-Standard Refined Diesel Fuel Oil on the Combustion Characteristics of a Diesel Engine and on the Environment

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Abstract:

The Niger Delta Region of Nigeria is presently inundated with non-standard refined diesel fuel oils, available in major towns and communities. To investigate the impact of burning these fuels, where no scientific evidence of their impacts is available, an experimental study was conducted to examine the effects of the non-standard refined diesel on engine performance and emission characteristics in comparison with standard refined diesel. The experiments were performed in a naturally aspirated, air-cooled, single-cylinder Cussons Engine Testbed, P8252, with a 3.5kW Lombardini engine. In this study, the engine was run at a constant speed of 2500 rpm with varying loads to replicate the typical usage of non-standard refined diesel fuels in generator engines in the Niger Delta Region of Nigeria. The exhaust emissions were analysed using a Testo 350 exhaust gas analyzer, and cylinder pressure was determined using a piezoelectric transducer. An Agilent Cary 630 FTIR spectrometer with an absorbance range of 4000 cm^{-1} to 650 cm^{-1} was used to identify functional groups within the fuel samples and the band equivalent to various radiations. Three non-standard refined diesel fuel oil samples obtained from the creeks of the Niger Delta Region of Nigeria, were tested along with a fourth sample of standard diesel obtained from a government retail outlet in Nigeria which was designated as the control sample. Results from the FTIR analysis indicated the presence of aromatic stretch around 1600 cm^{-1} for the non-standard refined fuel samples and the performance and emission analysis revealed low levels of brake thermal efficiency (BTE) with high levels of NO_x, CO, and CO_2 emissions for some of the locally refined samples.

Keywords **—** Compression ignition engine, Non-standard diesel, NO_x emissions, Carbon monoxide, Environment, Niger Delta Region

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I. INTRODUCTION

Diesel engines offer efficient combustion technology [EL-Seesy et al. 2019] and therefore, they are the main source of power in industries, ships, and small power generation plants [Sen, 2019], [Emiroğlu, 2019], [Tadros et al. 2019]. The diesel engine is also known for its high output torque and low consumption of fuel compared to the gasoline engine [Yu et al. 2020]. However, the emissions from the diesel engine have a harmful effect on the environment and humans [Santhosh et al. 2020], [Raman et al. 2019], [Mejia et al. 2020]. Based on a review from the World Health Organization (WHO), diesel engine exhaust emissions are classified as a carcinogenic substance [IARC, 2012].

Exhaust emissions from diesel engines have become a source of worry for many countries [Sadeq et al. 2019]. High levels of tailpipe emissions have led to stringent emission regulations especially for conventional diesel combustion engines [Lujan et al. 2019], [Elwardany et al. 2020]. Diesel engines are responsible for high particulate matter (PM) and nitrogen oxide (NO_X) levels in the environment [Benajes et al. 2020], [Sundaram et al. 2020]. The formation of NO_X in diesel engines is a function of the residence time, oxygen concentration, and combustion temperatures [Patil and Thipse, 2015].

Engines are designed and manufactured to operate on specified fuel [Ale, 2003], and the life of an engine is largely dependent on the quality of the fuel being used [Verma et al. 2018]. Refined diesel fuel oils, before being supplied to the market, are required to meet a set of regulatory requirements [Vempatapu and Kanaujia, 2017]. Sub-standard diesel fuel oil will not only affect engine performance, but it also increases the noxious emissions as well as greenhouse gases [Wang et al. 2020], and causes drops in engine pressure, difficulties in starting, and irreparable damage to engines [Cunha et al. 2016]. Also, [Bhowmik et al. 2019] reported that low quality diesel fuel oil reduces brake thermal efficiency (BTE) while it increases brake specific energy consumption (BSEC), carbon monoxide, and unburned hydrocarbon (UHC). The constituents in diesel exhaust emissions vary considerably depending on the fuel, lubricating oil, engine type, and operating conditions [Zielinska et al. 2004], [Nelson et al. 2008]. However, [Senthikumar et al. 2012] reported that emission reduction and performance enhancement in diesel engines could be achieved by the addition of fuel additives, engine modification, and exhaust gas post-treatment. Fuel modification could be achieved by increasing the percentage of oxygen in the fuel by the use of additives that are cost-effective, eco-friendly, and readily available [Kumar et al. 2020]. Several studies have been carried out on exhaust emission analysis of diesel engines using diesel fuel oil refined to meet standards and then blended with other fuels like kerosene, white spirit, tyre oil, nanoparticles, waste paint, and ethanol as presented in Table 1.

The quality assessment of diesel fuel oil is very important but comes at a very high cost while using standard methods [Nespeca et al. 2018]. Studies have shown that no technically straightforward solution has been developed in the petroleum industry to detect and identify compounds in substandard fuels [Adesina et al. 2020]. Fourier Transform Infrared Spectroscopy Infrared (FTIR) is a reliable and non-destructive method that provides a quick and straightforward analysis of a sample [Barra et al. 2019]. It determines fuel adulteration by measuring the absorbance bands of certain components in the fuel [Gong et al. 2016]. Spectra obtained from FTIR allow for functional group identification [Edney et al. 2020]. FTIR was used for the determination of biodiesel adulteration with raw vegetable oil [Soares et al. 2011], whilst [Barra et al. 2019] highlighted the dissimilarities between two diesel classes. The rapid and simultaneous prediction of eight quality parameters through FTIR analysis was highlighted by [Nespeca et al. 2018].

Nonstandard refining of crude oil is described as the method of refining petroleum products like gasoline, diesel, and kerosene without expertise or technology [Bebeteidoh et al. 2020]. These products are very common in the Niger Delta Region of Nigeria [Bebeteidoh et al. 2020]. In [Attah, 2012] the author described non-standard refineries as very inefficient, they produce low-grade diesel fuel oil and as much as 80% of the heavy end of the crude oil cannot be refined and is dumped into the environment. In [Nrior et al. 2018] it was reported that the non-standard refined products contain a lot of impurities and unsaturated hydrocarbons, which cause knocking in vehicles and generator engines, and have caused fires in residential houses. In [Patil and Thipse, 2015] the authors reported that non-standard refined diesel fuel contained adulterants, a higher than standard concentration of volatile organic compounds, and also had very low flashpoints.

TABLE 1: Literature review on diesel fuel blended with other fuels

Reference	**Fuel Blends**	**Findings**
[Kalligeros et al. 2005]	Diesel / Domestic heating oil/white spirit	Increased nitrogen oxide (NO_x), unburned hydrocarbon (HC), particulate matter (PM), a slight decrease in volumetric fuel consumption
[Czechlowski, 2020]	Diesel Fuel Oil	Increase in engine load results in a significant reduction in a significant reduction in specific NO_x emissions
[Yang et al. 2017]	Diesel /kerosene blend	Fuel with a higher percentage of kerosene gives maximum power output and lower carbon monoxide emission
[Patil and Thipse, 2015]	Diethyl ether/kerosene/diesel blend	Low brake thermal efficiency, high brake specific fuel consumption, high smoke at full load, low smoke at part load, low NO, almost similar CO, high HC, and low HC at part load
[Bodisco et al. 2019]	Diesel/tyre oil	No significant difference in NO_x emission. On-road NO_x emission significantly exceeded set regulations and significant variability in on-road emission.
[Bhowmik et al. 2017]	Diesel/kerosene/ethanol	The addition of ethanol to the diesel/kerosene blend substantially improved the brake thermal efficiency (BTE), brake specific energy consumption (BSEC), oxides of nitrogen (NO_x), total hydrocarbon (THC), carbon monoxide (CO) emissions of the engine
[Wani and Charoo, 2013]	Diesel/kerosene	Reduction in the brake specific fuel consumption and opacity with increased kerosene substitution in diesel
[Lee et al. 2013]	Diesel/waste engine oil/waste paint	Substantial increase in THC, NO_x, CO, PM, and CO_2. Also, high levels of VOCs (volatile organic compounds), benzene, toluene, ethylbenzene, and xylenes were recorded.
[Kadhim, 2011]	Diesel/kerosene	Reduced brake specific fuel consumption (BSFC). Increase in exhaust gas temperature, brake thermal efficiency (BTE), carbon dioxide (CO_2), NO_X
[Kumar et al. 2020]	Diesel/TiO_2 nanoparticles	By adding 50 and 100 ppm of TiO2 nanoparticles to diesel there was a significant reduction in CO, HC, NO_x, and smoke emissions
[Ithnin et al. 2018]	Water-in-Diesel emulsion	The result showed that emulsion fuel without surfactant does give significant improvement to the engine. There was also an increase in the BSFC compared to diesel fuel. Reduction in particulate matter (PM) and nitrogen oxide (NO_x)

Non-standard refined diesel fuel oil was used in this study. The diesel fuels were locally refined in the creeks of the Niger Delta Region of Nigeria using crude techniques [Bebeteidoh et al. 2020]. To produce non-standard refined diesel fuel oil, the crude oil was heated in 220 litre metal drums welded together to serve as pots [Umukoro, 2018]. The heated crude oil evaporates and goes through two pipes attached to the drums and placed inside a wooden water bath with the refined product emerging at the end of the pipe [Evbuomwan and Alete, 2020]. These refined products are classed as diesel fuel oil. A huge volume of these products has found its way into the Nigerian market, where unsuspecting customers buy them for their daily use in diesel-run small craft, generators, and vehicles.

The purpose of this study was to investigate the impact of the usage of non-standard refined diesel fuel oil on engines and the environment. Though cheap and readily available in the region, there is no scientific evidence of their impact available. The emission characteristics in terms of NO_x, CO, and CO_2, of the non-standard refined diesel fuel oil from three different camps in the creeks of the Niger Delta Region of Nigeria, and the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) were determined. FTIR technique was used to determine the chemical bonds present in the test fuels.

The rest of the paper is outlined as follows. Section II introduces the materials used and methodology. In Section III, the results and discussions are presented, while the effect of non-standard refined diesel fuel on the environment is presented in Section IV. Finally, the concluding remarks are given in Section V.

II. MATERIALS AND METHODS

A. Experimental Fuels and their Properties

The locally refined samples designated as A, B, and C were obtained from three different local refineries in the Niger Delta region of Nigeria. For comparison, a fourth sample, designated as D, is the control sample obtained from a government retail outlet in Port Harcourt, Rivers State, Nigeria. The physicochemical properties of the test diesel fuel oils are presented in Table 2 as adapted from [Bebeteidoh et al. 2020].

TABLE 2: Physicochemical properties of test fuels [Bebeteidoh et al. 2020]

Property	Units	A	B	C	D
Density	kgm^{-3}	850.7	854.5	854.4	862.8
Kinematic viscosity	mm^2s^{-1}	2.946	3.587	3.689	3.20
Water Content	mg/kg	77	87	214	78
Cetane Index		46.6	45.8	45.7	45.9

Samples A, B, and C are locally refined diesel fuel samples
D fuel obtained from a government retail outlet in Nigeria

B. Fourier Transform Infrared Analysis

The FTIR analysis was carried out to analyse the chemical bonds present in the test fuels. An Agilent Cary 630 FTIR spectrometer with an absorbance range of 4000 cm^{-1} to 650 cm^{-1} was used for the analysis to identify functional groups and the bands equivalent to various vibrations. Before measuring the spectral intensity, the sample holder was cleaned with acetone, and the CARY 630 FTIR instrument was connected to a computer with the software installed for data processing. Using a pipette, a sample was added to the sample holder and the spectra were captured. The infrared vibrational groups of the diesel fuel samples are shown in Table 3.

TABLE 3: Infrared Vibrational Groups of Diesel Samples [Nespeca et al. 2018].

Attribution	Wavenumber (cm^{-1})
CH_3 asymmetrical stretch	2953
CH_3 symmetric stretch	2870
CH_3 angular deformation	1379
CH_2 asymmetrical stretch	2922
CH_2 symmetrical stretch	2853
CH_2 angular deformation	1464
C=O carbonyl stretch	1750-1735
C-O stretch (aliphatic ester)	1300-1000
C=O stretch (aromatics)	1600 and 1475
=C-H stretch (aromatic)	900-690

C. Experimental Setup and Procedure

The experiment was conducted with a single-cylinder Cussons Engine Testbed P8252 with a 3.5 kW (4.8 Hp) Lombardini engine as illustrated in Fig. 1. The engine is a naturally aspirated fuel injected four-stroke compression ignition engine (CIE). The engine drives a 3-phase alternator via a toothed pulley and a toothed belt, has a 69mm bore cylinder, a 60mm stroke, and a maximum output of 3.5 kW

(4.8hp) at 3500 rpm. Specifications of the engine are listed in Table 4. This type of engine is most widely used for fishing boats and in the processing of farm produce around the coastal region of Nigeria.

To ensure that the engine was running in a steady-state condition during the tests, it was started and allowed to run under a no-load condition for 5-10 minutes. Tests were conducted at four different engine loads (0.12kW, 0.43kW, 0.95kW, and 1.71kW) and the rated speed of 2500rpm. The speed was held constant to mimic the operational profile of a constant speed standby generator and thereby determine the performance of the fuel in these generators. To ensure that the fuel system of the test engine was not contaminated by other fuels, a different external fuel tank, and fuel filter were used for each test case. At the end of each experiment, the fuel line was purged with clean diesel fuel, and the engine allowed to run for an ample time to consume any residual fuel from the previous experiment. This was to ensure that there was no contamination in the process of fuel replacement. The tests were conducted three times for each fuel sample. The repeatability analysis was based on the technical standard ISO/IEC 17025:2017 [Trishch et al. 2019], [LAI, 2019].

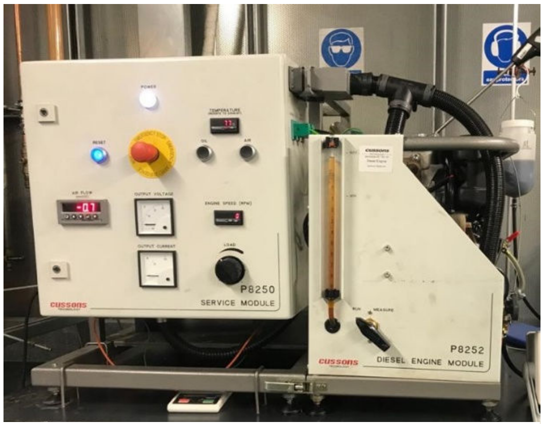

Fig. 1: Cussons Engine Test Bed P8252 with a 3.5 kW (4.8 Hp) Lombardini Engine.

TABLE 4: Specification of the Test Engine

Manufacturer Model	**P8252**
Engine type	4-stroke
Number of cylinders (N)	1
Bore (mm)	69
Stroke (mm)	60
Swept volume (cm^3)	224
Compression ratio	21.1
RPM	3600
Power (kW)	3.5
Fuel consumption (g/kW.hr)	267

A Testo 350 exhaust gas analyzer as illustrated in Fig. 2, was utilised to determine the concentrations of NO_x, CO, and CO_2 in the exhaust emissions. The Testo 350 analyzer is comprised of the sensor system and the electronics that are required for emission measurement. The specification of the Testo 350 gas analyzer is presented in Table 5.

Fig. 2: Testo 350 exhaust Gas Analyzer and Printer

A piezoelectric transducer (6052 Kistler high-temperature pressure sensor) was installed in the engine cylinder head to measure the in-cylinder pressure, and its output signal fed to a Type 5018A Kistler single channel charge amplifier. The signal from the single-channel charge amplifier was fed to a 100MHz GW INSTEK GDS-1102A-U Digital Storage Oscilloscope.

TABLE 5: Specification of the Testo 350 emission gas analyzer

Measurement Parameter	Range (ppm)	Accuracy	Resolution (ppm)
CO, H_2- Compensated	0-10000	±10ppm (0-199ppm) ±5% of mv (200-2000ppm) ±10% of mv (rest of range)	1
CO_{low}, H_2-Compensated	0-500	±2ppm (0-39.9ppm CO) ±5% of mv	0.1
NO	0-4000	±5ppm (0-99) ±5% of mv (100-1999.9ppm) ±10% of mv (2000-4000ppm)	1
NO_{low}	0-300	±2ppm (0-39.9ppm) ±5% of mv (40-300ppm)	0.1
NO_2	0-500	±5ppm (0-99.9ppm) ±5% of mv (100-500ppm)	0.1ppm

*mv stands for measured value

III. RESULTS AND DISCUSSIONS

Results from the FTIR are discussed in this section along with engine performance parameters including brake thermal efficiency and brake specific fuel consumption and the emission analysis.

1. FTIR Analysis

Fig. 3 illustrates the FTIR spectrum images for the four samples. The spectral peak around 2952 cm^{-1} appears in all samples and indicates the presence of asymmetric stretch CH_3 of a methyl group which can be found in diesel. A similar peak was reported by [Nespeca et al. 2018], [Barra et al. 2019], [Barra et al. 2020], [Li et al. 2020]. CH_2 is the most available functional group in standard diesel fuel, hence the most pronounced in the FTIR. The spectral peaks around wave numbers 2920 cm^{-1} and 2850 cm^{-1} are the asymmetric and symmetric stretch for CH_2 with a strong peak of its angular deformation appearing around 1457 cm^{-1}. All the samples analysed to show the presence of these spectral peaks which are all found in standard diesel fuel oil. This agrees with the work of [Nespeca et al. 2018], [LAI, 2019]. A trace of the spectral peak was identified around 1600 cm^{-1} which indicates aromatic stretch. All samples except D (standard diesel fuel oil) show the presence of this peak. This means that samples A, B, and C (non-standard refined diesel fuel oil) have a traceable amount of aromatic compounds such as benzene, toluene, and xylene (BTEX) [Barra et al. 2020]. This was also reported in [Ale, 2003] where there were high concentrations of toluene, and m-, p-, and o-xylenes, which was attributed to inadequate fractionation in the refining process. Various studies have reported the problems associated with the contamination of soil and water by BTEX [Ahmed et al. 2019], [Sun et al. 2021], [Kim et al. 2021], [Ashok et al. 2020]. BTEX contamination is serious because of its volatility, toxicity, solubility in water, and the ability to migrate [Ahmed et al. 2019]. BTEX contamination in soil has caused alarming issues in human health and ecosystems [Li et al. 2020].

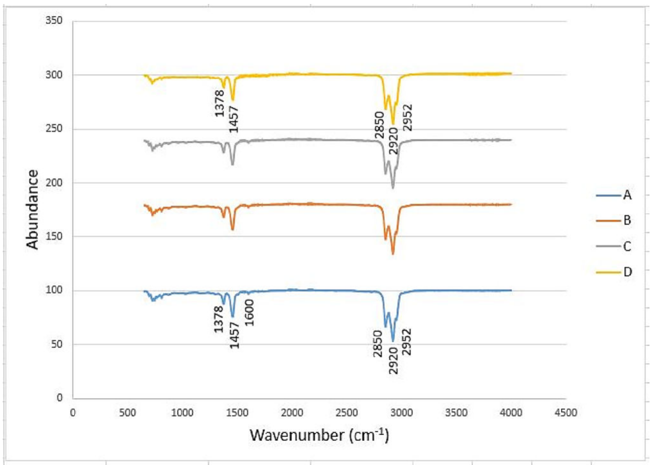

Fig. 3: Infrared spectra of all diesel samples

2. Brake Thermal Efficiency (BTE)

The correlation between the output power derived to the heat imparted in the engine is called brake thermal efficiency [Ashok et al. 2020]. It is used to evaluate how well an engine converts the heat from fuel to mechanical energy [Rahman et al. 2013]. The effect of the test samples A, B, C, and the control sample D on the brake thermal efficiency (BTE) at different load conditions is illustrated in Fig. 4. The brake thermal efficiency increased with the increase in load for all test samples. The BTE is superior at all loads for samples A and D. With increasing load there is a noticeable increase in the difference in the BTE between samples A, D, and B, C which could be attributed to higher fuel viscosity for samples B and C [Venu et al. 2020].

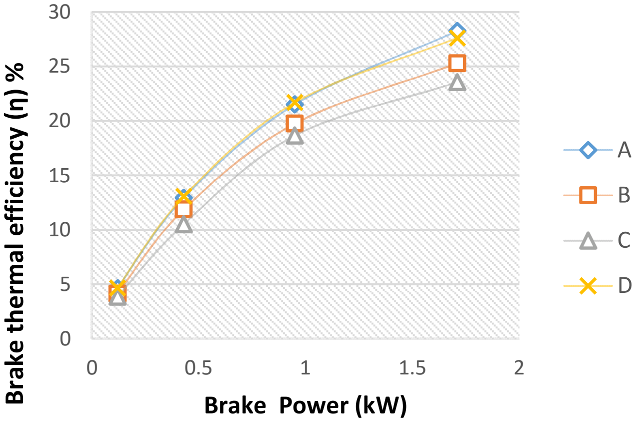

Fig. 4: Brake Thermal Efficiency (BTE)

3. *Brake specific fuel consumption (BSFC)*

The brake specific fuel consumption is defined as the quantity of fuel consumed for a unit power output [Hariram et al. 2020]. It is an important parameter to analyse the performance of the diesel engine [Shrivastava and Verma, 2020]. Change of BSFC at different loads for the test fuels A, B, C, and D is illustrated in Fig. 5. For all test cases, the BSFC increased with increasing load [Shrivastava et al. 2020], [Almohammadi et al. 2020]. The brake specific fuel consumption values for all test fuel samples is presented in Table 6. A slight difference could be observed between sample D and samples A, B, and C.

TABLE 6: Brake specific fuel consumption for test fuels

Engine Load (kW)	**Samples (kg/kW.hr)**			
	A	**B**	**C**	**D**
0.12	1.705	1.776	1.779	1.790
0.43	0.613	0.619	0.653	0.640
0.95	0.369	0.373	0.369	0.385
1.71	0.281	0.291	0.292	0.303

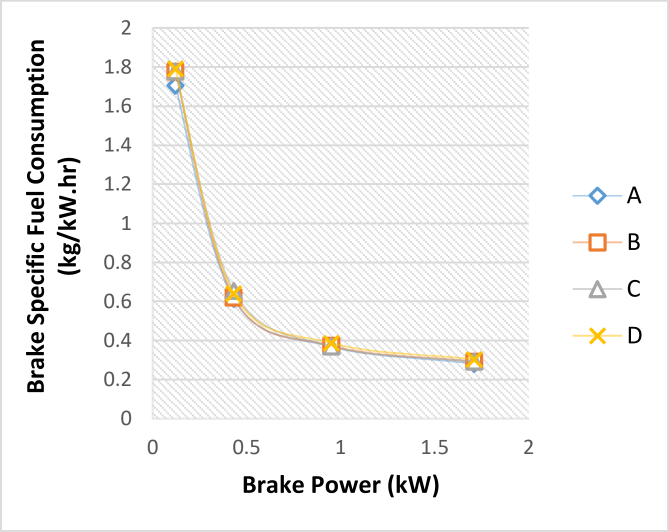

Fig. 5: Brake specific fuel consumption (BSFC)

4. *Oxides of Nitrogen (NOx) Emission*

Fig. 6 shows the variation in NOx emissions under different load conditions. As can be seen, the NOx emission increased with an increase in engine load for all the tested fuel samples. The non-standard refined diesel sample C had higher NOx compared to samples A, B, and the control sample D. Sample B had the lowest NOx value. The lower NOx formation indicated in sample B could be due to the lower temperature formed in the combustion chamber [Shrivastava et al. 2019]. Also, increased NOx in the test fuel samples could be attributed to aromatic content in the locally refined diesel fuel samples A, and C [Ale, 2003], [Sharma et al. 2020]. The NOx value for the test samples is presented in Table 7. Comparing the results of sample B to C, there was a 34.26%, 53.21%, 68.29%, and 33.79% increase in NOx emissions at the different load conditions. Also comparing the non-standard refined diesel fuel sample C to the control sample D, results showed an increase of 10.96%, 26.27%, 29.93%, and 27.64% in NOx emissions. The usage of non-standard refined fuel could lead to an increase in oxides of nitrogen which poses a great danger to humans and the environment [Lopatin, 2020]. NOx emission from diesel engines causes harm to human health, pulmonary problems, chest tightness, and chronic cough [Lopatin, 2020]. The effect of NOx emissions on the environment also includes ozone depletion, haze, acid rain, and the production of greenhouse emissions [Mohammadi et al. 2020].

TABLE 7: Oxides of nitrogen results for test fuels at varying loads

Engine Load (kW)	**Samples (ppm)**			
	A	**B**	**C**	**D**
0.12	264.73	226.93	304.67	274.57
0.43	352.37	286.87	439.50	348.07
0.95	552.87	402.30	677.03	521.07
1.71	791.53	696.80	932.27	730.37

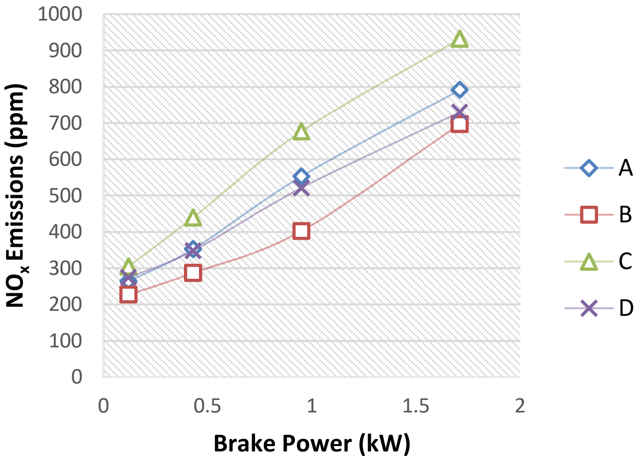

Fig. 6: Oxides of nitrogen (NOx)

5. *Carbon Monoxide Emission*

Fig. 7 shows the variation in carbon monoxide emission of the test fuels. A lack of oxygen during combustion could result in the formation of CO [Pan et al. 2019]. Samples A, C, and D had higher levels of CO emissions. Sample B on the other hand produced the highest CO emission at the highest load condition. The combustion temperature of an internal combustion engine could also affect the CO emission [Hazar et al. 2019]. In ICE, carbon monoxide emissions occur due to incomplete combustion [Yusri et al. 2019]. CO is a major environmental pollutant [Kalaimurugan et al. 2020]. It is one of the most significant pollutants and also the most harmful pollutant to human health [Liu et al. 2020]. It can be observed that carbon monoxide emissions decreased as the engine load increased in all the test samples. The CO emission value for test samples is presented in Table 8. There was an increase of 60.99%, 45.92%, 38.47%, and 41.59% between non-standard refined diesel fuel sample B and sample C. Also, comparing the control sample D with the non-standard refined diesel sample C, there was a percentage increase in carbon monoxide (CO) emission of 44.91%, 23.22%, 25.29%, and 29.08% at the four load conditions.

TABLE 8: Carbon monoxide results for test fuels at varying loads

Engine Load (kW)	**Samples (ppm)**			
	A	**B**	**C**	**D**
0.12	368.67	303.33	488.33	337.00
0.43	305.00	249.67	364.33	295.67
0.95	210.67	183.67	254.33	259.67
1.71	267.33	329.67	294.00	306.00

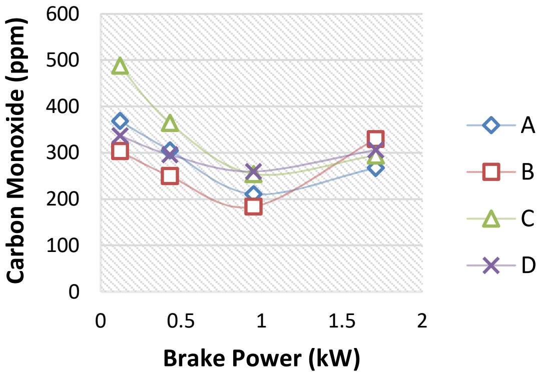

Fig. 7: Carbon monoxide (CO)

6. *Carbon Dioxide Emission*

Fig. 8 shows the variation in carbon dioxide emissions for the test fuel samples. This variation could be attributed to inconsistency in the refining process from the non-standard refineries A, B, & C. It can be seen from the figure that CO2 emission was highest for test sample C and lowest for sample B. With an increase in load, CO2 emission increased for all samples. The CO2 emission value for test samples is presented in Table 9. Increased CO2 emission aggravates the greenhouse effect, leading to global warming and human health risk [Harris et al. 2020].

TABLE 9: Carbon dioxide results for test fuels at varying loads

Engine Load (kW)	**Samples (%)**			
	A	**B**	**C**	**D**
0.12	2.07	1.77	2.46	2.02
0.43	2.52	2.12	3.25	2.46
0.95	3.49	2.79	4.23	3.46
1.71	4.77	4.61	5.74	4.64

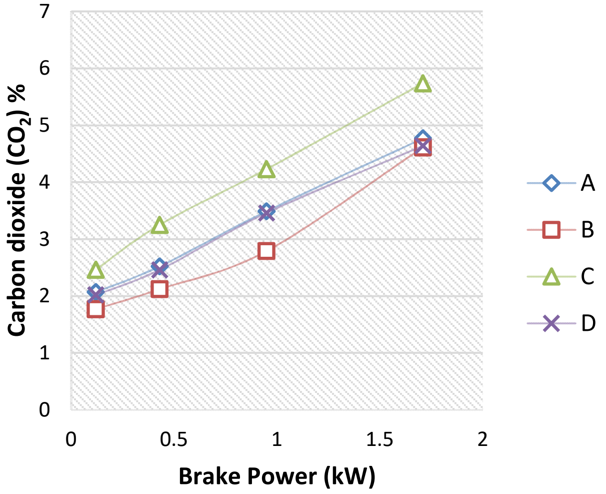

Fig. 8: Carbon dioxide emission (CO_2)

7. *Exhaust Gas Temperature*

The variations in the exhaust gas temperature (EGT) at different loads are illustrated in Fig. 9. Generally, there was an increase in the exhaust gas temperature with load for all the tested fuels. This could be attributed to an increased supply of fuel into the combustion chamber as a result of the higher load [Shrivastava et al. 2019]. The exhaust gas temperature also indicates the quality of combustion in the combustion chamber [Kalaimurugan et al. 2020]. The EGT for the test samples is presented in Table 10. It is dependent on the quantity of oxygen, the fuel-burning time, and pre-mixed fuel combustion time [Sharma et al. 2020].

TABLE 10: Exhaust gas temperature results for test fuels at varying loads

Engine Load (kW)	**Samples (°C)**			
	A	**B**	**C**	**D**
0.12	139.67	130.33	143.33	146.00
0.43	171.67	160.67	179.33	175.00
0.95	223.67	209.67	229.67	225.67
1.71	299.33	311.30	309.33	307.00

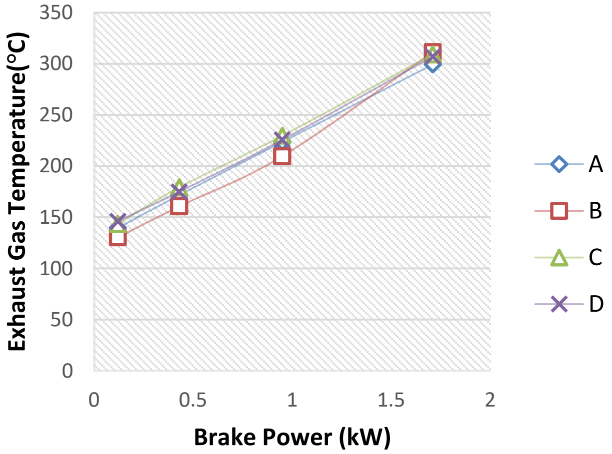

Fig. 9: Exhaust Gas Temperature

8. *Cylinder Pressure*

The difference in cylinder pressure under different loading conditions for all test fuels is presented in Fig. 10. There is a noticeable increase in cylinder pressure as the engine load in increased for all test fuels. At 0.12kW and 0.43kW brake power, the cylinder pressure of the non-standard refined diesel fuel oils was slightly higher than that of the control sample D. At 0.95kW brake power, sample C was slightly higher than the control sample D. At 1.71kW brake power, sample C was 3.35% higher than the control sample D. Comparing the cylinder pressure from the three different camps to that of the control sample as shown in Fig. 10 and Table 11, it was observed that at all load conditions the non-standard refined diesel fuel oil from camp C was higher than the control sample D. The higher pressure when using the non-standard refined diesel fuel oil may reflect shortened ignition delay time. According to [Ozer, 2020] the addition of solvents like toluene to diesel fuel oil results in shortened ignition delay; toluene reduces the flash, and ignition point of fuel. The addition of toluene is believed to start the burning in the first phase of the spray before the target point, possibly reducing the duration of the combustion [Simsek and Colak, 2019]. Due to its very low boiling point, toluene is easily gasified, and mixed with the charged air at the end of compression, could lead to a higher rate of combustion and higher cylinder pressure. The higher cylinder pressure could be damaging to internal engine parts like piston, piston rings and valves.

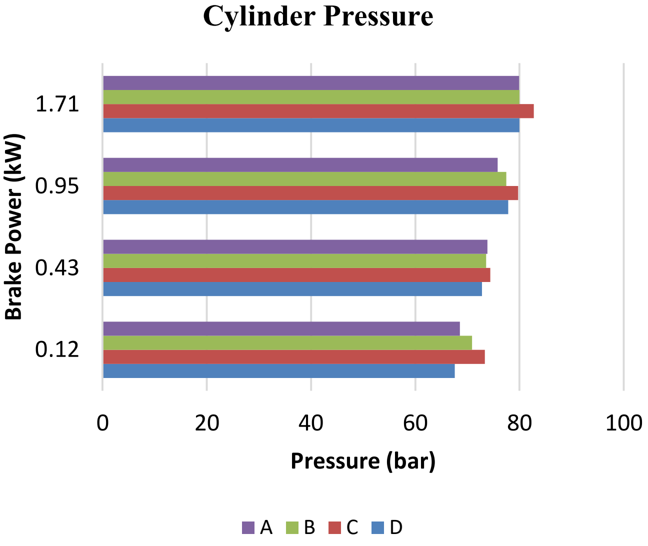

Fig. 10: Cylinder Pressure

TABLE 11: The percentage difference between the non-standard refined diesel fuel oils and the control sample at 1.71kW

Sample	Sample	% Difference Between
A	NGR	0.087
B	NGR	0
C	NGR	3.35%

IV. THE EFFECT OF NON-STANDARD REFINED DIESEL FUEL ON THE ENVIRONMENT

FTIR analysis of the tested fuel samples revealed the presence of aromatics in the non-standard refined diesel fuel oils compared to the control sample. VOCs which are characterized as unregulated emissions are much more dangerous to the environment and human health [Tian et al. 2018]. While VOCs can be from natural and anthropogenic origins, with natural sources mainly from vegetation emissions, volcanic eruptions, and forest fires the major anthropogenic sources comprise combustion and volatile emission [Niu et al. 2021].

In the controlled environment under which the experiment was conducted, there was a noticeable increase in harmful environmental pollutants from the usage of the non-standard refined diesel fuel oil. Results from the experimental analysis of the test fuels showed an increase in nitrogen oxide (NO_x), carbon monoxide (CO), and carbon dioxide emissions for samples A and C compared to sample B and the control sample. The increase in the level of these gases released into the environment could affect inhabitants and the environment of the Niger Delta Region where these fuels are refined and sold to the public at cheap rates. Nitrogen oxide emission is a source of acid rain, photochemical smog, stratospheric ozone depletion, tropospheric ozone formation, and even climate change [Tian et al. 2018], [Niu et al. 2021]. Also, an increase in carbon monoxide emission was observed from the results. CO is a component of motor vehicle exhaust and is found to be a small contributor in photochemical reactions leading to ozone formation and could cause pathological and physiological changes and untimely death in humans [Amid et al. 2020]. Results also revealed an increased level of CO_2 emission while using the non-standard refined diesel fuel oil with notable increases in samples A and C as compared to sample B and the control samples. With the world moving in the direction of reducing GHG emissions, to protect the environment, the continuous use of non-standard refined diesel fuel oil might lead to increased GHG emissions [Amid et al. 2020]. Finally, results also showed inconsistency in the non-standard refined products, which creates uncertainty when attempting to do corrective engine adjustments to burn these fuels. With this, the end-users of the products may not be getting value for monies spent.

V. CONCLUSION

The present study experimentally investigated the effect of non-standard refined diesel fuel oil on the environment and combustion characteristics of the diesel engine. The BTE, BSFC, cylinder pressure, and emission characteristics were obtained from the engine performance analysis while the chemical bonds present in the test fuels were determined using the FTIR. The conclusions can be summarized as follows:

1. The FTIR analysis indicated the presence of asymmetric stretch CH_3 of the methyl group which can be found in diesel. The most pronounced functional group was the asymmetric stretch of CH_2 with wavenumber 2920 cm^{-1} and 2850 cm^{-1}.
2. The FTIR analysis indicated the presence of a spectral peak of aromatic stretch around 1600 cm^{-1} for the nonstandard refined diesel fuel samples. Trace number of aromatic compounds such as benzene, toluene, and xylenes.
3. Decreases were found in the BTE for samples with higher fuel viscosity. There was no major difference in the BSFC for the samples at all test loads
4. NO_x emissions increased as the load increased for all the samples. The usage of non-standard refined fuel could lead to an increase in oxides of nitrogen which causes grave danger to the environment and humans.
5. CO_2 emissions increased as the engine load increased. Despite the engine's constant speed at 2500 rpm, the CO_2 emission for sample C was higher and sample B lower compared to samples A and D. The variability in the CO_2 emissions could be attributed to the inconsistency in the refining process. Increased CO_2 emissions aggravate the greenhouse effect.
6. The high cylinder pressure from sample C could be damaging to piston rings, pistons, and valves.

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