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Comparative Study of Exhaust Emissions from Diesel and Syngas Powered 3.5 kW Compression Ignition Engine with and without Load

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Abstract

Despite diesel engines being highly efficient, with low fuel consumption and reduced carbon dioxide emissions, they emit relatively high levels of particulate matter and oxides of nitrogen (NO_x) due to high exhaust gas temperatures. Engine emissions show the quality and completeness of combustion. This paper aims to present the results of a study comparing exhaust emissions from a diesel and syngas powered engine. Syngas was produced from co-firing coal and biomass in a gasifier then cleaned, cooled and applied as an alternative fuel in an engine operated from 0 - 100% load. Exhaust-emissions were monitored at this load conditions. The exhaust-temperature was measured using thermocouples and the emission gases were analyzed using Testo 350. The emissions were lower and decreased as the engine load increased, except for sulphur dioxide and NO_x. The study shows that levels of carbon monoxide, were higher in a range of 46.5 - 80.2%, while carbon dioxide was 3.3 - 18% higher compared to those from diesel. Hydrocarbon emissions were 480 and 1250 ppm for diesel and syngas respectively. The study reveals that the engine operates optimally at higher loads since hydrocarbons and oxides of carbon are low due to complete combustion at higher temperatures. Exhaust gas temperature was higher in the syngas fuel and increased as the engine load increased in the range of 455.83 - 480.03˚C which influenced the formation of NO_x. NO_x from diesel was found to be higher, ranging from 32.5 - 40.5%, compared to those from syngas with an engine load of 75%. The study observed that relative to diesel, the emissions of sulfur dioxide at 50% engine load were lower in a range of 23.7 - 57.1%. Emissions of hydrocarbons depended on the degree of substitution of diesel and engine load. The study therefore shows that, relative to diesel, emissions decreased when syngas was used with upgraded syngas from *Prosporis juliflora* presenting as the best alternative followed by *Hyphanae compressa*, and lastly rice husk. For optimal performance of the syngas fuelled engine, the study reports that the engine should be operated at engine loads above 50% with strategies on NO_x emissions considered.

Keywords

Emissions, Engine Load, Temperature, Neat-Diesel, Syngas

1. Introduction

Energy is a key contributor to social and economic growth in a country and determines people's living standards [1]. The transition from non-renewable to renewable energy has remained a challenge in the modern world [2]. Diesel, a non-renewable energy is extensively used in the transport sector due to its proven higher energy density compared to the same volume of gasoline. Despite studies reporting diesel engines to have various advantages such as engine power superiority, energy density, and fuel economy, limitations such as engine durability and emissions have been raised [3] [4]. Diesel emissions have been associated with global warming as well as causing respiratory and cancerous disorders [5] [6]. The International Agency for Research on Cancer (IARC), a division of the World Health Organization, classified diesel exhaust, particularly particulate matter, as a carcinogens [4] [5] [7].

A possible technology to lower emissions is by converting diesel engines to run on syngas and pilot diesel (dual fuel) [8]. Syngas has a much wider ignition range than conventional hydrocarbon fuels, so it can be burned leaner, reducing CO emissions and particulate matters (soot or smoke) when compared to the burning of diesel. Several researchers found that syngas as a dual fuel reduces pollution caused by NO_x, SO_x, and soot emission, but an increase in CO emission is noted [9]. CO is a colorless, odorless, and poisonous gas formed in the combustion chamber as a byproduct of combustion due to insufficient oxygen and represents lost chemical energy. When there is insufficient oxygen, poor fuel atomization or distribution across the combustion chamber, or even insufficient time for the reaction, some fuel remains unburned (unburnt hydrocarbons), leading to its production.

Combustion of hydrocarbons should produce CO_2 and water, but because of incomplete combustion, unburnt hydrocarbon emissions are produced which are carcinogenic as well as irritant odorants. On the other hand, carbon dioxide, CO_2, a combustion product is a greenhouse gas [6]. Parameters such as exhaust gas temperature (EGT) can be used in comparative studies of different engines operated in the same or different fuels [10]. EGT is a meaningful parameter as it represents various performance parameters in the combustion chamber such as the formation of oxides of nitrogen [11]. Equation (1) and Equation (2) can be used to estimate the rate of formation of NO_x and UHC emissions [12] [13].

$$\frac{d\left(No_x\right)}{dt}=\frac{6\times 10^{16}}{T^{\frac{1}{2}}}\exp^{\left(\frac{-69,090}{T}\right)}\left[O_2\right]^{\frac{1}{2}}_{e}\left[N_2\right]_e \tag{1}$$

Where $[O_2]_e$ and $[N_2]_e$ denote species concentrations at equilibrium in moles per cubic centimeters and can be determined from the gas analyzer and T is the maximum absolute temperature in the combustion chamber as read from the thermocouples.

$$\frac{d\left(HC\right)}{dt}=-6.7\times 10^{16}\exp^{\left(\frac{-18,733}{T}\right)}\dot{x}HC\dot{x}O_2\left(\frac{P}{RT}\right)^2 \tag{2}$$

where $\dot{x}HC$ and $\dot{x}O_2$ are the mole's fractions of HC and O_2 respectively also obtained from the exhaust gas analyzer and t is time in seconds.

The formation of NO_x depends on the combustion temperature. NO_x is mainly composed of nitrogen monoxide, NO, and nitrogen dioxide, NO_2, which causes ecosystem acidification [14]. At temperatures above 1100°C, nitrogen combines with excess oxygen to form NO_x [15]-[17].

NO_x emissions are influenced by factors such as cylinder pressure, temperature, excess oxygen and residence time [18]. A study by Singh & Maji [19] found that at higher CR, in syngas fueled engines, NO_x increases proportionally as the load increases due to the increased heat energy released from the fuel. Boehman & Corre [14] and Tomita *et al.* [20] reported Exhaust Gas recirculation (EGR) as an effective tool to reduce NO_x emission. Other strategies to reduce NO_x emission include the use of catalyst reduction, steam injection, or water injection, after the injection of the pilot fuel. Refitting and modification of the engine coupled with adjustments is another strategy. In their study, Gatumu *et al.* [21] suggested some minimal modifications and adjustments, such as the injection timing (IT) to 25.2 degrees before the top dead center (which increased the duration of fuel in the cylinder) and selecting an optimal CR of 18 with the inclusion of a T-pipe connector to supply the two fuels.

CO emissions decrease as the compression ratio and engine load increase due to less diesel fuel being injected as diesel is replaced with a clean burning fuel [8] [15]. Studies have reported a 3% decrease in emissions when the compression ratio was adjusted from 15 to 18 since there was better combustion and a reduction in ignition lag [22]. A study by Sayin and Canakci [23] reported that when IT was retarded by 6^0 crank angle before top dead center (CA bTDC), NO_x emissions decreased by 37.3% under 50% engine load conditions. Other studies reported similar results, noting that retarded IT reduced maximum pressure and temperature since there was enough fuel available for combustion after TDC thus lower emissions [24]-[26].

The present study focuses on emission analysis on a modified and retrofitted engine using upgraded syngas in comparison to neat diesel emissions.

2. Materials and Method

The study was carried out experimentally on a modified and retrofitted direct injection and compression ignition engine. The bench scale fixed bed gasifier generated upgraded syngas from optimized blends of ratio 1:1 weight by weight for coal and selected biomass (*H. compressa,* rice husk and *P. juliflora*), coded as HC, RH, and PJ respectively. The upgraded syngas was cleaned, cooled, and used to power a 3.5 kW, modified, and retrofitted test engine at a speed of 1500 revolutions per minute. The test engine was a naturally aspirated, water cooled, direct injection compression ignition engine, Kirloskar make, Model-TV1 with geometrical parameters such as 110 mm stroke length, 80 mm bore diameter, and 661 cc displacement volume [27]. The safety of pipes, gasifier, and engine joint connections was checked using the GS 5800 ultrasonic leak detector with room ventilation also considered by opening all windows and doors to avoid carbon monoxide poisoning. All other safety procedures were strictly followed.

Fuel properties of neat diesel and upgraded syngas are shown in **Tables 1-2**. The properties of syngas were measured in triplicate and the average was obtained. Standard deviation was also determined with an analysis of variance conducted. Statistical significance was carried out by applying Tukey's and Scheffe's test.

Table 1. Upgraded syngas composition.

Syngas composition	PJ	HC	RH	*P. value*
Carbon monoxide (%)	24.75 ± 0.56^{a}	23.8 ± 0.01^{b}	20.89 ± 0.78^{c}	0.04^{S}
Hydrogen (%)	22.23 ± 0.04^{g}	18.7 ± 0.72^{h}	14.23 ± 0.08^{i}	0.305^{nS}
Carbon dioxide (%)	10.21 ± 0.32^{d}	9.8 ± 0.02^{e}	15.54 ± 0.44^{f}	0.04^{S}
Methane (%)	2.23 ± 0.07^{j}	2.2 ± 0.86^{k}	5.23 ± 0.06^{l}	0.00 ^{S}
Nitrogen and other gases* (%)	40.58 ± 0.12^{m}	45.5 ± 0.59^{n}	44.11 ±0 .18^{o}	0.00^{S}
Calorific value (MJ/m^3)	4.97 ± 0.10^{p}	4.78 ± 0.13^{q}	4.61 ± 0.09^{r}	0.02^{S}

S: significant, ns: nonsignificant, significance difference at 5% applying Tukey's and Scheffe's test are indicated using the same letters in a row, **means the values are obtained by differences.*

Table 2. Properties of upgraded syngas and neat diesel (Source Mustafa [31] and Nduku [32]).

Fuel parameter	Quantity value
Diesel density (25˚C)	845 kg/m^3
Diesel flow rate	4.56×10^{-7} m^3/s
Calorific value of diesel	42 MJ/kg
Air and upgraded syngas rate to test the engine	4.43×10^{-3} m^3/s
Air and upgraded syngas temperature at engine inlet	29.0˚C
Upgraded syngas and air density	0.95 kg/m^3

Engine exhaust gases were passed through engine calorimetry, which was coupled with thermocouples (type K) and data logger (Advantest model TR2724) for exhaust gas temperature measurements [13]. Syngas does not auto ignite and usually a small amount of diesel is supplied through a mechanical governor at the tail end of the compression stroke to assist and boost combustion [28]. Furthermore, the study considered the optimal CR at 18 and injection timing of 25.2 degrees before the top dead centre (bTDC), since studies have reported that increasing CR from 12 to 18 and advancing engine IT causes a decrease in EGT at an optimal speed of 1500 rpm [9] [21] [29]. These studies attributed this decrease to an increased period of fuel in the combustion chamber and uniform mixing of fuels, which allows complete combustion to occur.

Testo 350 emission analyzer probe was inserted into the exhaust sampling port of the calorimetry for data collection and analysis [30]. The built-in software in Testo 350 and the exhaust sensors with the specification and accuracies shown in **Table 3** made it possible to collect and send the data to a computer for storage and further analysis. The engine was loaded according to the equipment manual with data collected at an interval of two minutes according to the ISO 8178 test cycle for engine load at 0, 3, 6, 9 and 12 (0%, 25%, 50%, 75% and 100%). Purging was performed after every load to recalibrate the exhaust gases sensors. The engine emissions concentration was measured and recorded. The experimental setup is shown in **Figures 1-2**. **Figure 3** shows the experimental methodology presented as a flow chart.

Table 3. Testo 350 gas analyser specifications (Source Testo, [30]).

Gas sensor	Type of sensor	Composition range	Percentage accuracies
O_2 (%)	infrared	Up to 21%	±2
Carbon monoxide (ppm)	infrared	0 - 5000	±10 for less than 400 ppm and ±5 for greater than 400 ppm
Carbon dioxide (ppm)	infrared	0 - 2000	±0.3
Unburnt hydrocarbon (%)	infrared	0 - 21%	±10
Oxides of nitrogen (ppm)	electrochemical	0 - 5000	±5
Thermocouple type K (˚C)		Up to 1000	±3

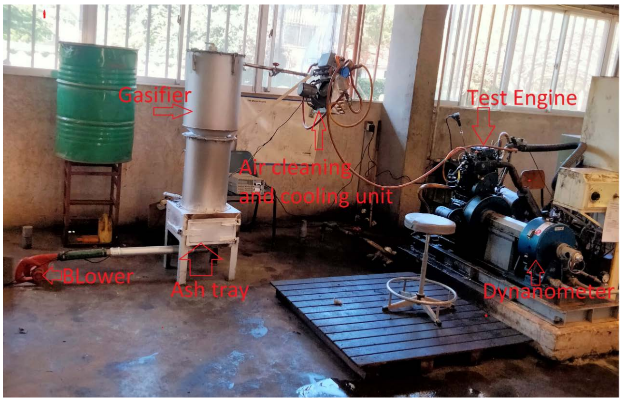

Figure 1. Experimental setup.

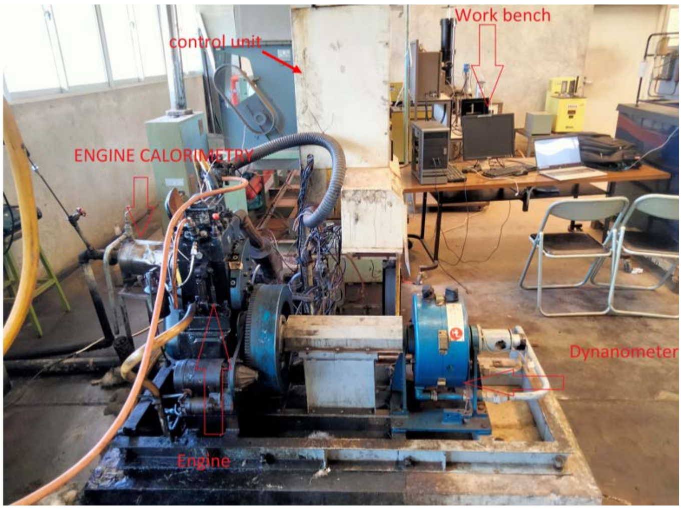

Figure 2. Set-up of emission and exhaust gases data collection.

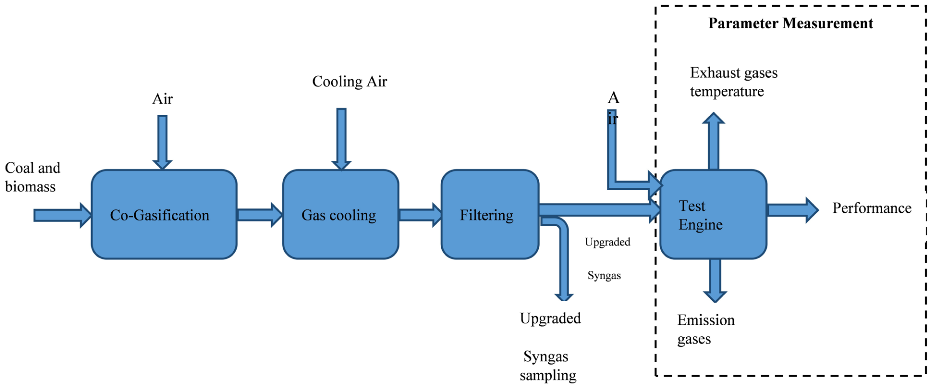

Figure 3. Experimental methodology flow chart.

3. Results and Discussion

The experimental data is discussed based on exhaust gas temperature and emission analysis.

4. Exhaust Gas Temperature (EGT) Variations with Engine Load

The current study reports a maximum exhaust gas temperature (EGT) of 476.96˚C, 455.83˚C, 480.03˚C, and 475.26˚C for *P. juliflora,* neat diesel, rice husk, and *H. compressa*, respectively, when the engine was operated at 100% engine load. **Figure 4** presents the variation of the EGT with the engine load.

From **Figure 4**, EGT steadily increases as the engine load rises for both neat diesel and the syngas-diesel fuel mode. The observed trend is due to the increased fuel requirement (both syngas and pilot diesel) to produce the additional power needed to manage the extra load, which leads to higher exhaust gas temperatures (EGT). Additionally, the rise in EGT is due to the sufficient time available for combustion between diesel and syngas, resulting from advanced injection timing, which ensures complete combustion.

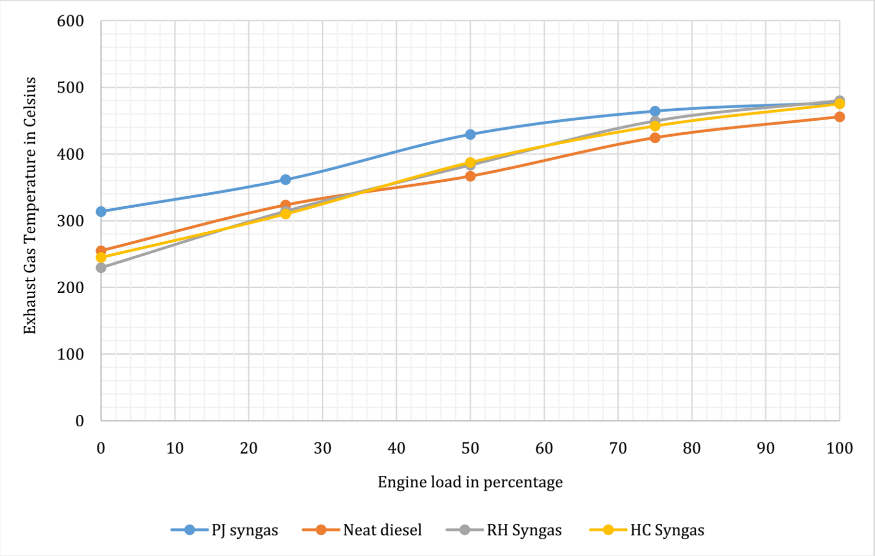

Figure 4. Variation of exhaust gases temperature with engine load.

The EGT for *P. juliflora* is the highest, with neat diesel being the lowest. The syngas-diesel fuel mode had a higher EGT due to lower calorific values in syngas, resulting in extended combustion during exhaust stroke. The present study agrees with other researchers.

Murthy *et al.* [33] conducted a study on a syngas powered engine and found that at higher loads, the exhaust temperature rises with an increase in the flow rate of the LPG. They attributed this to the higher LPG flow rate, which, when fully combusted, gave higher exhaust gas temperatures. Furthermore, they noted that when the injection timing was advanced, a higher cylinder temperature was recorded, which consequently increased exhaust gas temperatures and NO_x levels. Similarly, a research reported a 42% increase in EGT when the engine was operated on syngas than when diesel was used at CR of 18 [21]. They attributed this rise to the additional energy provided by both syngas and pilot diesel fuel.

Furthermore, they suggested that the presence of slow-burning syngas might have led to some portion of unburned mixture leaving the combustion chamber to the exhaust system, where it combusts, resulting in higher EGT. Shrivastava *et al.* [34] similarly reported that when diesel was operated at full load it had an EGT of 330˚C and the dual fuel mode had a higher EGT than diesel. They attributed these results to the extra energy available in the syngas-fueled engine. Lal & Mohapatra [9] reported an EGT of 330˚C for diesel mode and 380˚C for dual fuel under full load conditions. To reduce EGT in combustion engine, a study reported that the optimal approach was to increase the density of the fuel mixture (*i.e.* more mass entering the combustion chamber for the same volume) [24]. Kamal *et al.* [26] conducted experiments with a supercharged compression ignition engine operating on syngas fuel. Their study recorded higher exhaust gas temperature values for the supercharged syngas-pilot diesel fuel setup, which they associated with improved and increased air-fuel density.

5. Composition and Levels of Combustion Emissions

The variations in emission with engine load for diesel and upgraded syngas fuel samples are shown in **Figures 5-9**.

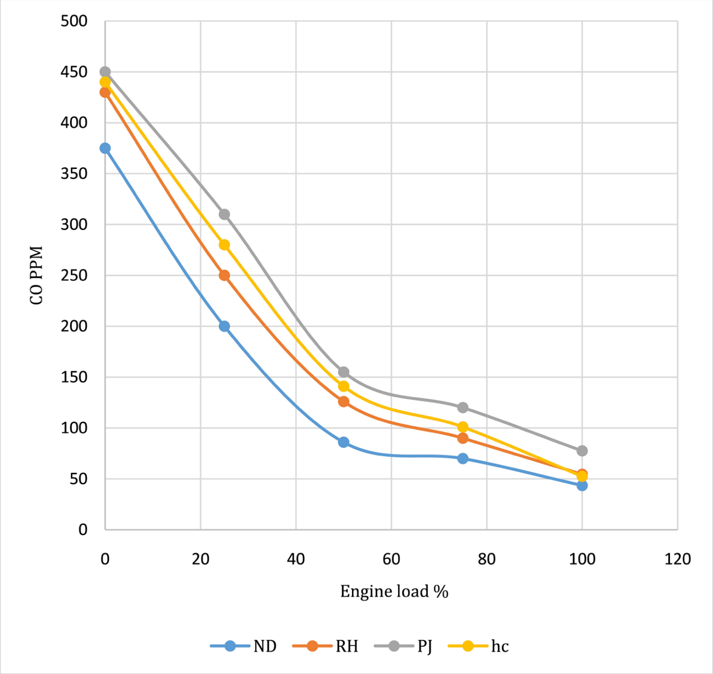

Figure 5. Variation of carbon monoxide with engine loads.

6. Carbon Monoxide Variation with Engine Load

Figure 5 shows that CO emission decreases as the engine load increases, with the highest reported CO concentration being 375 ppm in neat diesel and 450 ppm in upgraded syngas under no load conditions. At CR of 18 ND had a low percentage of CO, followed by blends of RH, HC, and finally PJ. CO emissions were found to be 46.5% to 80.2% higher in the upgraded syngas-fueled mode than in the neat diesel mode at 50% engine load. As the load increases from zero to 100%, the emissions reduce due to more fuel required, thus a rich air-fuel mixture enters the engine cylinder to maintain the speed and torque requirement. Because of the rich air-fuel mixture, the combustion is complete, and fewer carbon monoxide emissions are released. The results also indicate that carbon monoxide emissions are higher in the upgraded syngas fuel mode compared to a neat diesel-fueled engine. This was attributed to the lower oxygen content in the air-syngas mixture, which causes incomplete combustion.

Shrivastava *et al.* [34] observed a similar trend, reporting a maximum CO concentration of 10 and 250 ppm in diesel and syngas fuel, respectively. Ramadhas *et al.* [35] noted maximum CO concentrations of 700 and 1300 ppm in diesel and syngas fuel respectively. For a CR of 18 and an engine load of 80%, Sombatwong *et al.* [36] found that the maximum carbon monoxide emissions was 500 ppm in syngas fuel and 100 ppm in diesel fuel. Pradhan *et al.* [37] in their review on internal combustion engine (ICE) emissions, observed that various researchers had indicated higher carbon monoxide emissions in syngas-fueled engines both at low and moderate loads. They attributed the higher levels of CO in syngas fuel mode to the presence of CO in syngas fuel, which could have been left out during combustion.

However, they noted that these emissions decreased with increasing engine load, which they attributed to improved fuel conversion efficiency. Various studies attributed the higher emission of carbon monoxide in dual fuel engines to incomplete combustion in the cylinders due to insufficient air, leading to oxygen deficiency [23]. Another study reported Carbon monoxide emissions were 300 ppm in diesel fuel and 1025 ppm when the engine was operated on syngas [9].

7. Variation of Nitrogen Oxides with Engine Load

Figure 6 presents the variation of nitrogen oxide in ppm with the engine load as a percentage.

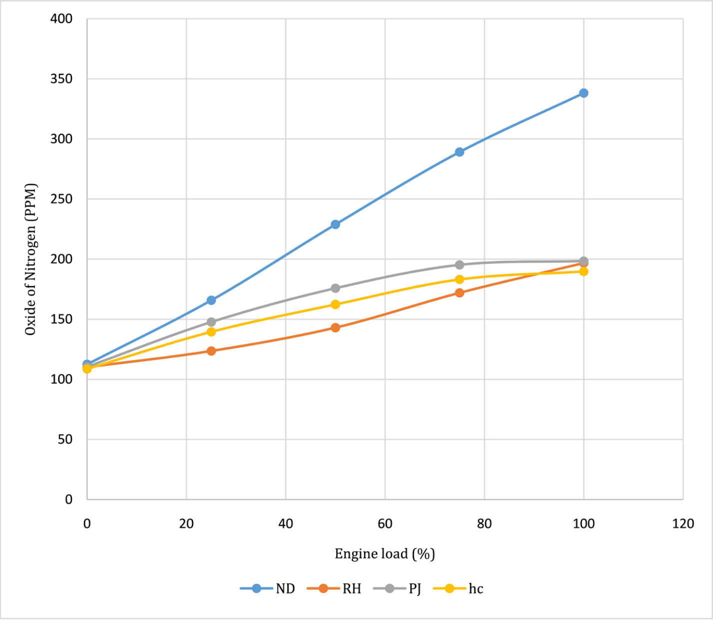

Figure 6. Variation of nitrogen oxides (ppm) with engine charge (%).

Under no load conditions, an insignificant difference in NO_x emission was observed while the engine was operated on neat diesel and upgraded syngas fuel. As the load increases, NO_x emission increases in neat diesel at a range of 32.5 to 40.5% higher than upgraded syngas at a 75% engine load. The maximum concentration of NO_x at full load was found to be 338.17 ppm for neat diesel (ND), 196.77 ppm, 189.71 ppm and 198.38 ppm for RH, HC and PJ, respectively. For 75% engine load, the maximum concentration of NO_x was found to be 289.14 ppm for ND, 172 ppm, 183.07 ppm and 195.24 ppm for RH, HC and PJ respectively. The lower values of NO_x emission obtained in upgraded syngas were due to less intense premixed combustion, which causes low flame propagation in the fuel-air mixture because of excess upgraded syngas and lower levels of oxygen (air displaced by upgraded syngas) in the cylinder, leading to lower temperatures in the combustion chamber. At a higher compression ratio, the rise in NO_x emissions observed when the engine load was increased is due to more fuel injected, as well as to the higher cylinder temperatures and pressures, which promoted the formation of NO_x species. A previous study highlighted that higher cylinder temperatures, adequate oxygen levels, and sufficient reaction time, favored the formation of NO_x emissions [38].

Shrivastava *et al.* [34] reported comparable findings, reporting peak values of oxide of nitrogen emissions of 180 ppm in syngas fuel and 325 ppm in diesel engines at 75% engine load. A study reported a higher emissions level of NO_x to be 904 ppm for the syngas-fueled engine when operated at 80% load condition [39]. They associated this with a higher temperature in the cylinder caused by higher fuel injected at higher engine loads. A study by Yaliwal *et al.* [40] reported maximum NO_x emissions of 110 ppm in a syngas-fueled engine under an engine load of 80%, while Lal & Mohapatra [9] reported a maximum concentration of 13 to 80 ppm in syngas fuel mode and 393 ppm in diesel mode. To reduce oxides of nitrogen, EGR can be applied in the engine. Typically, this process involves redirecting small portions of exhaust gases back into the intake manifold, where they blend with the incoming air. This action decreases the peak combustion temperatures and pressures, subsequently lowering NO_x emissions [33]. The reintroduced exhaust gas displaces a portion of the standard intake charge, which moderates and cools the combustion process, ultimately diminishing NO_x formation. However, reintroducing exhaust gases into the engine combustion chamber may have adverse effects on engine performance and durability due to oil and exhaust gases contaminations and degradation.

Studies have reported that EGR of 15% effectively reduces NO_x emission without much adverse effects on the performance (around 2.17% reduction in break thermal efficiency) [3] [33]. According to a study by Murthy *et al.* [33] they noted a decrease in brake thermal efficiency, which was associated with combustion degradation, stemming from lower combustion temperatures and changes in the air-fuel ratio, which resulted to reduced oxygen concentration.

8. Variation of Unburned Hydrocarbons at Various Engine Loads

Figure 7 presents the variation of unburnt hydrocarbons (UHC) in ppm with varying engine load (%).

Figure 7 clearly shows that UHC emissions are lower for neat diesel and higher for upgraded syngas, as the upgraded syngas displaces the inducted air. The UHC decreases as the engine load increases since the temperature and pressure increases as the engine load increases, and thus better combustion is attained. Shrivastava *et al.* [34] reported similar trends. The present study noted that UHC emissions are 1250 ppm in upgraded syngas fuel and 480 ppm in diesel. At a CR of 18 and under 80% load conditions, Shrivastava *et al.* [34] found the highest concentration of unburnt hydrocarbons (UHC) to be 15 ppm in diesel and 20 ppm in syngas fuel. Dhole *et al.* [41] reported UHC emissions of 2400 ppm in syngas fuel, while Banapurmath & Tewari [42] noted UHC emissions of 46 ppm in syngas fuel.

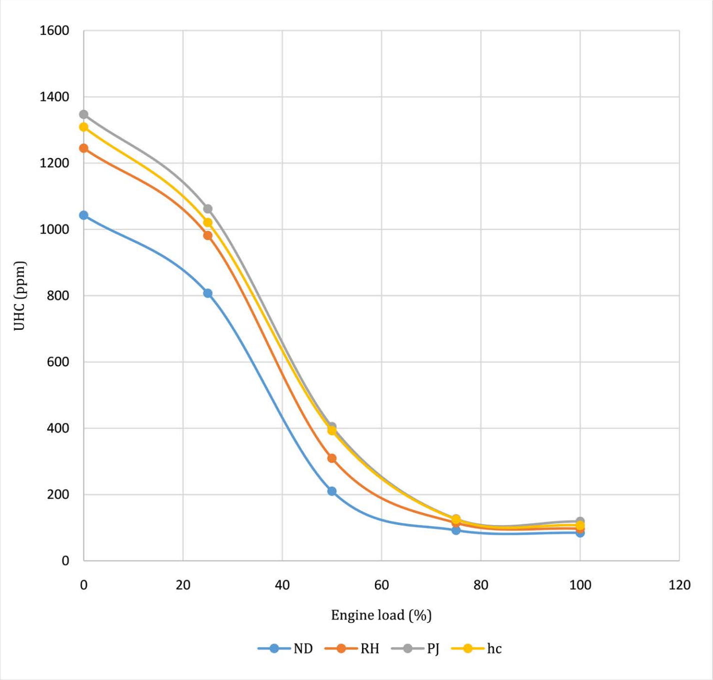

Figure 7. Variation of UHC in ppm with engine load (%).

Studies have reported that the concentration of UHC in exhaust gases decreases as the engine load increases with dual fuel reporting lower values than diesel [19]. A similar study by Gatumu *et al.* [21], reported that in neat diesel at CR 18, the UHC emission decreased by 78%, when the engine load increased from zero to 100% engine load. These trends were attributed to the lack of uniform temperature distribution and homogeneity of the air fuel mixture in the cylinder (some local spots in the combustion chamber were too lean for proper combustion and the other spots were too rich) [21] [23] [28].

9. Variation of Carbon Dioxide Emission with Engine Load

Figure 8 shows that CO_2 emissions increase as the engine load increases, in a range of 3.3% to 18% higher than neat diesel. Singh & Maji [19] and Ahmed *et al.* [43] reported similar trends in diesel and syngas-driven engines. This behaviour was attributed to the composition of the upgraded syngas which contains some CO_2. Furthermore, at high compression ratio, as the load increases, the pressure of the cylinder and the temperature also increase, leading to better fuel combustion, and thus an increase in carbon dioxide emissions. The findings of the current study align closely with those reported in the existing literature. For instance, at CR of 18, Singh *et al.* [17] observed a maximum carbon dioxide emission of 7.76% in syngas-pilot diesel and 3.63% in diesel mode, while Sahoo *et al.* [44] noted a maximum carbon dioxide emission of 6.2% in dual fuel mode and 8.0% in diesel mode. Additionally, Lal & Mohapatra [9] indicated that CO_2 emissions in syngas mode relative to diesel were 6.0% to 33.72% higher at 80% engine load.

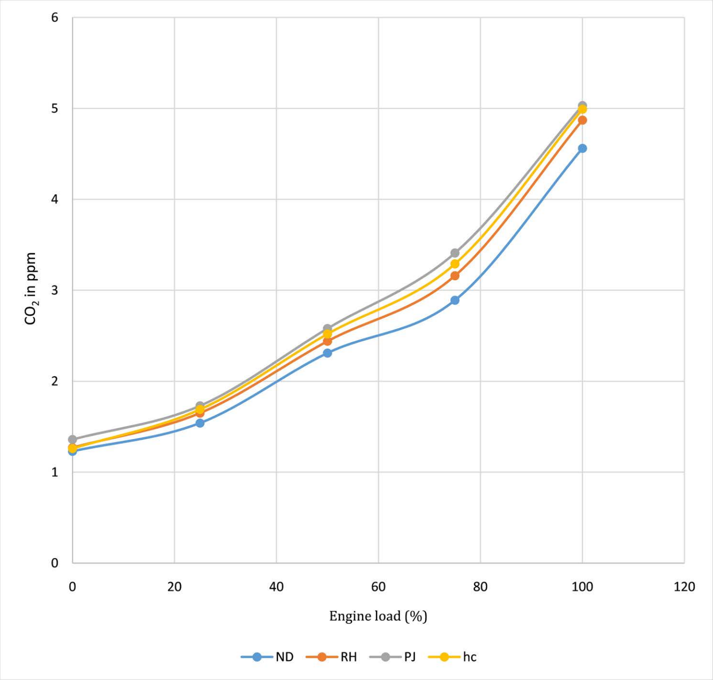

Figure 8. Variation of carbon dioxide emission with engine load.

10. Variation of Sulfur Oxides for Various Engine Loads

The variation in sulpur oxides (SO_x) emission under different engine load conditions in diesel mode and in upgraded syngas mode is presented in **Figure 9**.

From **Figure 9** it is evident that SO_x emission increases as the engine load increases. This was attributed to the fact that as the load increases, the engine requires additional fuel to sustain the additional load. The emissions from SO_x reported in the present study under full load conditions were 7.30 ppm, 3.22, 3.40, and 3.90 for ND and blends of RH, HC and PJ respectively. Furthermore, at 50% engine load the SO_x emissions level in syngas fueled engine were lower relative to neat diesel in a range of 23.7 - 57.1%. For an engine load of 80% and an optimal CR of 18, Saleh [45] reported the highest SO_x emissions at 25 ppm, while Tan *et al.* [46] noted a maximum SO_x emission concentration of 4.6 ppm. Lal & Mohapatra [9] reported SO_x emissions in dual fuel at CR 18 to be 54.54% lower than neat diesel at 80% engine load (3.2 kW). For full load conditions, they also reported SO_x emission of 6.8 ppm for neat diesel and 4.1 ppm for syngas dual fuel mode.

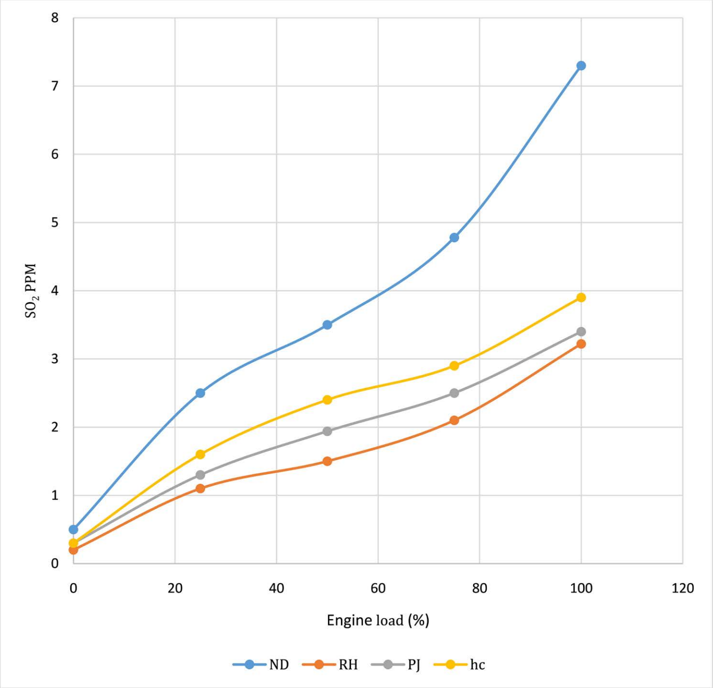

Figure 9. Variation of SO_2 with engine load.

11. Conclusion

The upgraded syngas when used as an alternative transport fuel relative to neat diesel produces lower acidic emissions (oxides of sulfur and nitrogen) and thus lower environmental pollution. The study shows that unburnt hydrocarbon and oxides of carbon are higher at low engine loads and decrease as the load increases since complete combustion occurs. In fact, CO emissions were observed to be 46.5% to 80.2% higher in upgraded syngas than in neat diesel at 50% engine load. The present study reports emission levels of 1250 ppm in diesel and 480 ppm in upgraded syngas. The lower values of oxide of carbon and unburnt hydrocarbon as the engine load increased was a result of an increase in temperature which was noted at a range of 455.83˚C to 480.03˚C at full load conditions. The resulting increase in exhaust temperature as the engine load increased also caused NO_x emission to increase in a range of 32.5 to 40.5% lower than neat diesel for upgraded syngas at 75% engine load. To reduce EGT and NO_x, exhaust gas recirculation can be applied in combination with the injection of water into the engine chambers. CO_2 emissions also increase as the load increases, as expected, in a range of 3.3 to 18% higher than neat diesel implying that combustion was complete. For SO_x emission, at 50% engine load, the study reveals that emission levels were lower than neat diesel in a range of 23.7 - 57.1%. Therefore, the study presents upgraded syngas from PJ, HC, and RH as the best alternative fuel compared to neat diesel when the engine is operated above 50% engine load and has an optimal speed of 1500 rpm. The scope of the research study was limited to emissions analysis on compression ignition engines fueled by the novel upgraded syngas. However, research on spark ignition engines fueled by upgraded syngas can be conducted in the future to characterize emissions and engine performance.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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