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EXHAUST EMISSION CHARACTERISTICS OF A GARDENER COMPRESSION IGNITION ENGINE FUELLED WITH RAPESEED METHYL ESTER AND FOSSIL DIESEL

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ABSTRACT
This paper presents an experimental investigation into the exhaust emissions characteristics of a gardener Compression Ignition (CI) Engine fuelled with rapeseed methyl Esther (RME) and fossil diesel under lean equivalence ratios (0.2≤ φ ≤0.8). The experiments were carried out at engine speeds of 750 and 1250 rpm under five different loads. The experimental results showed that NO_x and CO_2 emissions increased while emissions of HC, O_2 and CO decreased with increasing equivalence ratio, exhaust temperature, brake mean effective pressure and specific fuel consumption. All exhaust emissions were found to decrease with increasing engine speed from 750 to 1250 rpm. There was reduction in exhaust emissions of RME over fossil diesel by 0.06% for O_2, 84% for CO and 4.7% for CO_2 at 750rpm. At higher speed of 1250rpm however, RME was observed having higher NOx and CO_2 but relatively lower O_2 and CO than the fossil diesel.

Keywords*— Exhaust Emission, Compression ignition engine, rapeseed methyl Esther, engine speed, fossil diesel*

1. INTRODUCTION

For centuries, internal combustion engines either fuelled with gasoline or diesel fuels have immensely been supporting human endeavours. Latest statistics of the world oil proved reserve, production and consumption data as revealed by the British Petroleum [1] is shown in Table 1. Consumption of fossil fuels as shown on the Table is still on the rise despite various advances in producing much cleaner alternative fuels. For example, the world oil consumption has increased by 12.5% over the last decade (2008 to 2018) primarily due to growth in population and intensification of economic activities. Although the current proved reserve of the world oil currently stands at 244.1 billion tonnes/annum, two challenges are imminent. First, Organisation of Petroleum Exporting Countries (OPEC) could decide skyrocketing the global oil prices due to huge pressure (demand) on the reserve. Second, this demand action could also deplete the reserve and global environmental pollution is likely to increase. Fuels emanating from renewable sources have been found by several researchers to be much cleaner and most sustainable alternatives. Production of these alternative fuels from biological sources (biofuels) is usually carried out to augment such high fuel demand. Several feedstocks have been used by many researchers to produce biofuels. For example, Deka and Basumatary [2] produced sulphur free biodiesel from yellow oleander with the biodiesel having cetane number of 61.5. Others include Jathropa curcas [3], Neem Seed [4], Coconut Ethyl Ester [5] etc.

Performances of the biofuels in an engine are documented and exhaust emissions generated by burning biofuels mostly in compression ignition engines have also been analysed extensively. For example, Senatore *et al*. [6] carried out comparative analysis of combustion processes in direct injection diesel engine fuelled with diesel and rapeseed methyl ester (RME) under fuel rich regime (equivalence ratio (φ) of 1.0 – 4.0). Senatore *et al*. found that Diesel fuel had higher CO and emissions than RME with RME having higher NOx emissions in the fuel rich regime. Papakianakis *et al*. [7] studied the effect of dual

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fuelling (natural gas + diesel) and diesel fuels on the exhaust emissions. They found that exhaust emissions were reduced by about 50% especially at low and intermediate loads depending on engine operating conditions. With this emission reduction in mind, Zhang *et al*. [8] recently investigated the effect of low-level water addition on the combustion and emission characteristics. They found that adding low-level water up to 4wt% to diesel and RME significantly reduced exhaust emissions especially for NOx, CO and CO_2. Despite these contributions by researchers on biofuels, especially RME, there is hitherto little studies concerning the emission characteristics of RME in comparison with fossil diesel under lean conditions. The influence of combustion parameters on the exhaust emissions under low and high engine speeds are also rarely studied.

This paper therefore reports an experimental investigation into the exhaust emissions of Gardener Compression Engine fuelled with diesel and Rapeseed Methyl Ester under various loads and low and high operating speeds. Comparative analysis of the exhaust emissions of CO_2, CO, HC, O_2, NOx for both diesel and RME was carried out. Influence of engine parameters such as brake mean effective pressure (Bmep), equivalence ratio (φ), specific fuel consumption (SFC) on the exhaust emissions was also reported.

2. EXPERIMENTAL SYSTEMS AND METHODOLOGY

The Gardener engine with model no 1L2, is a four-stroke, single cylinder, direct injection compression ignition engine which is used to determine the influence of various fuel types at different experimental conditions. The engine has swept volume (Vs) which is 12 times the clearance volume (Vc). The Gardener engine used has four injector nozzles each with diameter of 220 µm and injector opening pressure of 16.2 MPa. Table 2 shows the full specifications of the Gardener 1L2 engine used for the experiment.

Table 1: World Oil Statistics 2019

Region	Proved Reserve 10^9 t/yr (2018)	Production 10^6 t/yr (2018)	Consumption 10^6 toe/yr (2018)	Consumption 10^6 toe/yr (2008)
North America	35.4	1027.1	1112.5	1105.3
South and Central America	51.1	335.1	315.3	287.9
Europe	1.9	162.9	742.0	817.1
CIS	19.6	709.1	193.5	174.7
Middle East	113.2	1489.7	412.1	351.1
Africa	16.6	388.7	191.3	156.5
Asia Pacific	6.3	361.6	1695.4	1250.2
World	244.1	4474.3	4662.1	4142.9

Source: [1]. *1toe =7.33 barrels. toe=tonnes of oil equivalent, t=tonnes*

Table 2: Gardner Engine Specifications

Parameters	Specifications
Model	1L2
No cylinders	(σ) 1
Bore (*D*)	07.95 mm
Stroke (*S*)	152.4 mm
Swept volume (capacity)(V_s)	$1394.8 \times 10^{-6}\ m^3$
Clearance volume (V_c)	$115.15 \times 10^{-6}\ m^3$
Compression ratio	14:1
Max. power	14.4 kW @ 1500 r/min
Inlet valve opening	10° btdc

Parameters	Specifications
Inlet valve closing	40° abdc
Exhaust valve opening	50° btdc
Exhaust valve closing	15° atdc
Injection timing	24.5° btdc
Injector nozzles	4
Nozzle throat dia	220 µm
Injector opening pressure	16.2 MPa

Where: atdc = after top dead centre, btdc = before top dead centre, abdc= after bottom dead center, bbdc = below bottom dead center

2.2 Experimental Procedure

The experiment was carried out by taking readings at engine speeds of 750 and 1250rpm for a typical RME (*rapeseed methyl ester*) biodiesel and fossil diesel fuels. The engine was operated under five loads (4, 8, 12, 16 and 18 kg). Atmospheric pressure was initially measured at room temperature using a manometer mounted on the engine when a load of 4kg was applied on the engine at a speed of 750rpm. The manometer measured the height of mercury in millimetre (mm). The engine speed was set and measured using *analogue tachometer*. Fig.1 shows a schematic of the experimental set up.

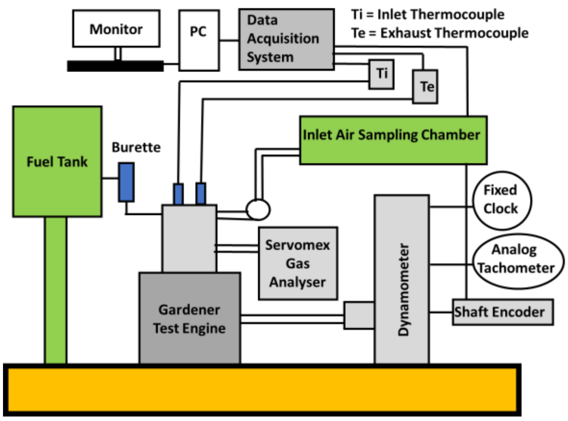

Fig. 1: Schematic of the Experimental Set-up

The inlet and exhaust temperatures were measured with a *thermocouple* while the time taken (in seconds) for the engine to consume 20ml of RME and diesel fuels was measured with a *fixed clock* mounted on the engine. The volume of the fuel was noted using a burette attached to the fuel tank. The Gardener engine was connected to a *Desktop computer* via a data acquisition system where the pressure readings (fuel line pressure, cylinder pressure and TDC positions) and exhaust temperature were measured. Emission readings of Carbon monoxide (CO), Carbon dioxide (CO_2) and excess oxygen (O_2) were measured and recorded from Servomex 4210C gas analyser. A Signal 4000VM chemiluminescence analyzer was used to measure NOx emission, while unburnt hydrocarbon (HC) emissions were measured by a Rotork Analysis model 523 flame ionization detector (FID) analyser. Both analysers sampled exhaust gas via a heated line at 160°C. The procedure was repeated for the remaining loads and for diesel fuel and all at a speed of 1250rpm. All the afore-mentioned readings were also noted and recorded. Tables 3, 4, 5 and 6 show the inlet and exhaust readings recorded for RME and diesel fuels at engine speeds of 750 and 1250rpm.

3. RESULTS AND DISCUSSION

3.1 Comparison of RME and Diesel Inlet and Exhaust Emissions Parameters

Tables 3 and 4 show values for the inlet and exhaust parameters at a speed of 750rpm for RME and fossil diesel fuel respectively. Tables 5 and 6 show values for the inlet and exhaust parameters at a speed of 1250rpm for RME and fossil diesel fuel respectively. For the engine inlet parameters, it can be seen from the four tables that the manometer readings decreased with increasing engine load from 4 – 18kg regardless of the fuel tested and for the speeds of both 750 and 1250rpm. For example, combustion of RME at a speed of 750rpm and inlet temperature of 13°C showed a reduction of manometer reading by 15% while combustion of diesel at the same speed and inlet temperature of 13°C showed reduction of manometer reading by only 10%. At a relatively higher engine speed of 1250rpm, the manometer readings were seen increasing for both fuels. On the other hand, variations of exhaust temperatures with increasing loads was observed to have an increasing trend and the exhaust temperatures were observed to be increasing with engine speed from 750 – 1250rpm. The time to consume 20ml of RME and diesel fuels for combustion was also found decreasing with engine loads.

Looking at Tables 3,4,5 and 6 for the raw exhaust emission data captured from the Sevomex 4210C gas analyser, it can be seen that emissions in excess oxygen, O_2 (%), carbon II oxide, CO(%) and unburned hydrocarbon, HC(ppm) decreased with increasing loads for both RME and diesel fuels while emissions of Oxides of Nitrogen (NOx) increased with increasing load. These trends were also observed by Imran *et al.* [9]. In comparison with emissions from burning RME with combusting fossil diesel, RME was observed to have lower exhaust emissions than fossil diesel at the engine speed of 750rpm and at all the loads tested. At higher speed of 1250rpm however, RME was observed to be having higher NOx and CO_2 but relatively lower O_2 and CO than the fossil diesel. These results are consistent with those reported by Sentore *et al.* [6], but under rich equivalence ratios. Merkisz *et al.* [10] also reported RME having higher concentration of NOx emissions than fossil diesel fuel, and the emission quantity did not change even after using the exhaust gas after treatment system. For instance, at a load of 4kg and engine speed of 750rpm, there was reduction in exhaust emissions of RME over fossil diesel by 0.06% for O_2, 84% for CO and 4.7% for CO_2. Previous studies also reported reduction in CO, O_2 and CO_2 but some under rich equivalence ratios [11- 13]. The implication of these observations is that RME can be a better substitute for a fossil diesel in a CI engine especially at low speed.

Table 3: RME parameters at speed of 750 rpm at inlet temperature of 13°C

Inlet Parameters					
Mass (kg)	4	8	12	16	18
Exhaust Temp (Tex), °C	140.7	190.2	236.3	303.4	329.9
Manometer height (mm)	19.5	18.5	18	17.5	16.5
Fuel time - t (s)	122	86.67	64.86	50.56	45.23
Exhaust Emissions					
O_2 (%)	16.67	14.4	12.12	9.73	8.03
CO (%)	0.14	0.11	0.07	0.06	0.05
CO_2 (%)	2.81	4.4	6.07	7.75	8.86
NO_x (ppm)	297	580	823	995	920
HC (ppm)	390	400	290	240	280

Table 4: Diesel parameters at speed of 750 rpm at inlet temperature of 11°C

Inlet Parameters					
Mass (kg)	4	8	12	16	18
Exhaust Temp (Tex), °C	139	184.0	226.9	292.8	331.56
Manometer height (mm)	19.5	19.0	18.5	18.0	17.5
Fuel time - t (s)	128	88.62	66.97	50.28	43.56
Exhaust Emissions					
O_2 (%)	16.84	14.84	12.57	9.74	8.74
CO (%)	0.89	0.504	0.372	0.257	0.280
CO_2 (%)	2.95	4.44	6.07	8.01	9.33
NO_x (ppm)	279	609	955	1210	1270
HC (ppm)	133.2	130.7	121.9	72.8	60.2

Table 5: RME fuel results at speed of 1250 rpm at inlet temperature of 14°C

Inlet Parameters					
Mass (kg)	4	8	12	16	18
Exhaust Temp (Tex), °C	183.18	232.81	293.01	371.37	383.43
Manometer height (mm)	46	45	43.5	41.5	37.5
Fuel time - t (s)	67.61	47.92	37.13	28.98	26.1
Exhaust Emissions					
O_2 (%)	15.89	13.71	11.21	8.05	7.47
CO (%)	0.12	0.1	0.008	0.08	0.09
CO_2 (%)	3.58	5.23	7.12	9.46	10.27
NO_x (ppm)	373	271	936	980	1045
HC (ppm)	323.3	277.7	254.1	239.5	264.4

Table 6: Diesel parameters at speed of 1250 rpm at inlet temperature of 17°C

Inlet Parameters					
Mass (Kg)	4	8	12	16	18
Exhaust Temp (Tex), °C	164.16	209.36	263.14	338.4	364.5
Manometer height (mm)	49	45.5	45.5	44	43.5
Fuel time - t (s)	73.79	51.64	39.01	30.26	29.17
Exhaust Emissions					
O_2 (%)	16.65	14.47	12.12	9.0	8.11
CO (%)	0.888	0.6	0.008	0.08	0.09
CO_2 (%)	3.15	4.72	6.39	8.47	8.8
NO_x (ppm)	196	585	970	1268	1308
HC (ppm)	108.5	127.1	96	50.1	49

3. 1 Variations of Exhaust emissions with equivalence ratio

This section reports variations of exhaust emissions with equivalence ratio (φ) normalised with values computed from the specific fuel consumptions (SFC). Variations of equivalence ratio with carbon (iv) oxide emission is presented in Fig.2a. It can be observed from Fig.2a that CO_2 emission increased with an increase in equivalence ratio (φ = 0.2 -0.8). With increasing operating speed from 750 -1250rpm, the CO_2 emission was found to decrease. This behaviour of increased CO_2 emission is not surprising since increasing the equivalence ratio means introducing more carbon-based fuel into the engine and therefore CO_2 emission as one of the principal combustion products is also expected to increase. However, Fig.2b represents a graph for the emissions of carbon monoxide (CO) with equivalence ratio. It can be seen from the graph that increasing equivalence ratio (φ) from 0.2 to 0.8 limits the production of CO drastically, especially at a speed of 750rpm. CO emission was also reduced at higher speed of 1250rpm at equivalence ratios ranging from 0.2 – 0.48. The result for the decreased CO emission signifies near complete combustion for RME.

Fig.2c shows the variations of oxygen emissions with equivalence ratio. Like the trend of CO emissions, oxygen (O_2) emission was also observed decreasing with increasing equivalence ratio regardless of the engine operating speed. This is expected since increased equivalence ratio signifies increased fuel consumption. This consequently leads to the use of most air (O_2) in the combustion chamber leaving only small amount of excess O_2 to be emitted. Taking closer look at Fig.2c, the difference on the influence of the two engine speeds on the O_2 emission at φ = 0.3 remains insignificant. Equivalence ratio of 0.3 shows that the O_2 emission of 2200g/MJ is the same at both speeds of 750 and 1250rpm. This Margin of O_2 emission slightly increased to 250g/MJ, with the 750rpm at slightly higher speed. Fig.2d shows variation of unburned hydrocarbon (HC) emissions with equivalence ratio. It can be seen from the graph that increase in equivalence ratio results in corresponding decrease in HC emissions. This trend continues until at φ = 0.5 in which the trend reverses. Production of HC is also triggered by incomplete combustion as results of uncontrolled vaporization of fuels. Imran *et al.* [9] also reported variations of HC emissions similar to those in this work.

Nitrous oxide emissions (NOx) has been shown to vary with equivalence ratio in Fig.2e. It is apparent from Fig.2e that NOx production is triggered at lower speed with increased equivalence ratio. This also buttress that the higher the engine speed, the lower the tendency of NOx emissions. For example, at ultra-lean equivalence ratio of 0.3, the NOx emission is 9.0g/MJ and it reduced to 8.0g/MJ when the speed was increased to 1250rpm. At higher equivalence ratio approaching stoichiometric, say φ = 0.6, the NOx emission was seen increasing significantly to 11.4 g/MJ at 750rpm and reduced remarkably to 8.7g/MJ when the speed was increased to 1250rpm.

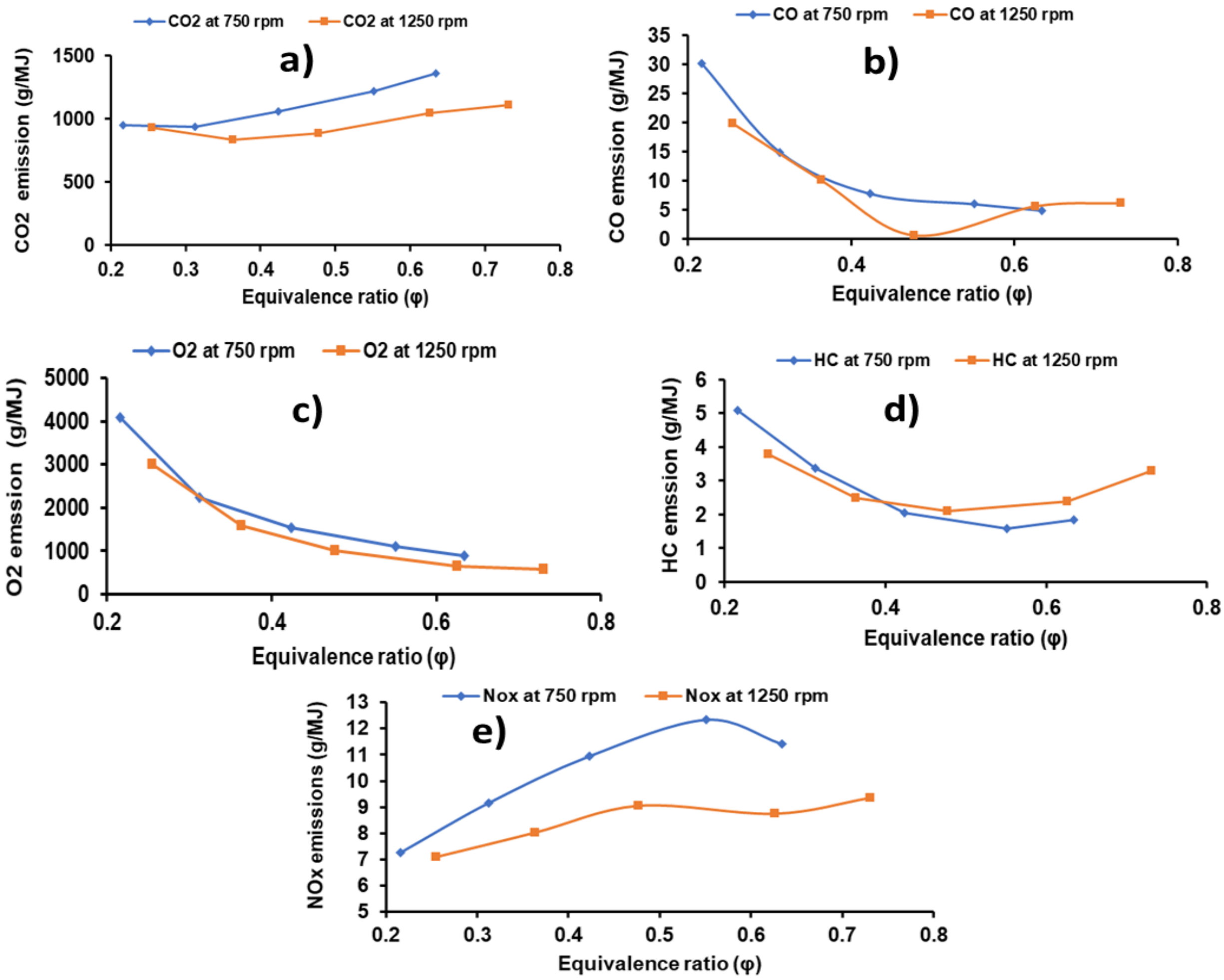

Fig.2: Variations of exhaust emissions with equiablence ratio (φ) a) CO_2 b) CO c) O_2 d) HC e) NOx

3.2 Variations of Exhaust emissions with Bmep

Fig.3a shows a graph for the variations of CO emissions with brake mean efffective pressure (bmep). It can be seen from Fig.3a that, at a speed of 750rpm, CO_2 emissions increased from 931 – 1359 g/MJ when bmep increased from 0.13 to 0.57MPa. Similar trend for CO_2 emissions can be seen at a speed of 1250rpm although at lower concentrations. Fig.3b shows the graph of the variations of CO emissions with bmep. The figure rather shows decreasing trend of CO emissions with increasing bmep especially for loads of 4 -12kg with the speed of 750rpm having higher CO emissions. This behaviour is in line with previous studies [14], A turning point can be seen from Fig.3b at a load of 12kg where CO emissions started increasing for both speeds. Fig.3c and 3d demonstrate variations of bmep with O_2 and HC emissions respectively. It can be seen from both graphs that increasing Bmep within the range of 0.13 - 0.57MPa resulted in increase in O_2 and HC emissions, with the emission values at engine speed at 750rpm higher than those at 1250rpm. This variation of Bmep with O_2 and HC emissions is also similar with those of CO emission.

Fig.3e shows the variations of NOx emissions with bmep. It can be observed from the figure that the NOx emissions increased with increasing bmep especially for the three loads (4 – 12kg) and for all the engine speed tested. For loads ranging from 16 – 18kg, there seemed to be slight decrease and increase in NOx emissions for speeds of 750 and 1250rpm respectively. Taking closer inspection of Fig.3e, NOx emissions were found to be higher with speed increase from 750 – 1250rpm. Crookes and Bob-Manuel [14] also reported increased NOx emission with increasing Bmep from 0.2 to 0.5MPa for both RME and DME fuels.

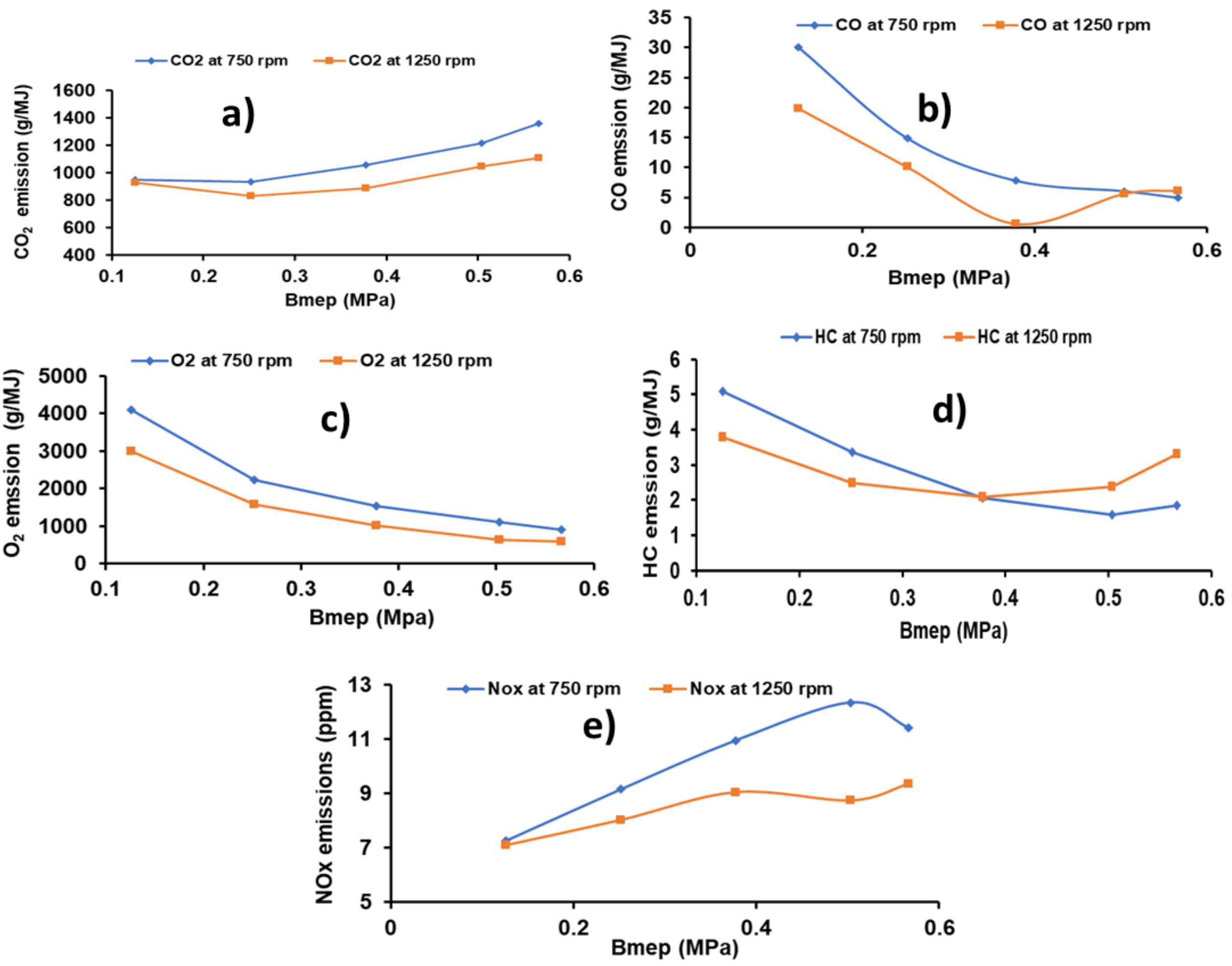

Fig.3: Variations of exhaust emissions with brake mean effective pressure (Bmep) (φ) a) CO_2 b) CO c) O_2 d) HC e) NOx

3.3 Variations of Exhaust emissions with Specific Fuel Consumption (SFC)

Fig.4 shows variations of representative exhaust emissions with specific fuel consumption (SFC). Fig.4a shows the variations of carbon mono oxide (CO) emissions with SFC. It can be seen from Fig.4a that CO emissions decreased with increasing engine speed from 750 to 1250rpm irrespective of the engine load. Fig.4a also demonstrates that CO emissions becomes more pronounced at higher specicific fuel consumption and it drastically reduced with increasing engine load. At the speed of 750rpm for instance, CO emissions was found to be 30g/MJ at a load 4kg and it markedly decreased to 4.9g/MJ (84% reduction) at the highest load of 18kg. Fig.4b shows the variations of emissions levels of O_2 with the SFC at speeds of 750 and 1250rpm for the four different loads. It can be observed from Fig.2b that O_2 emissions decreased with increased engine speed from 750 to 1250rpm regardless of the engine load. On the other hand, when more fuel was consumed (higher SFC), the emissions levels of O_2 is seen to be the highest. The explanation to this phenomenon is basic. As more fuel is consumed, more oxygen is needed for complete combustion. When the exact quantity of oxygen is consumed and burnt, the excess oxygen is then emitted as shown in Fig.4b.

Fig.4c presents the emissions of oxides of Nitrogen (NOx) with SFC. It can be seen from Fig.4c that NOx emissions increased with decreasing SFC and increasing engine load at the two speeds tested. The figure also showed that NOx emission was slightly higher at 750rpm than at 1250rpm regardless of the engine load. This trend of increasing NOx for RME has also been seen already in Fig.2e (with equivalence ratio) and Fig.3e (with brake mean effective pressure).

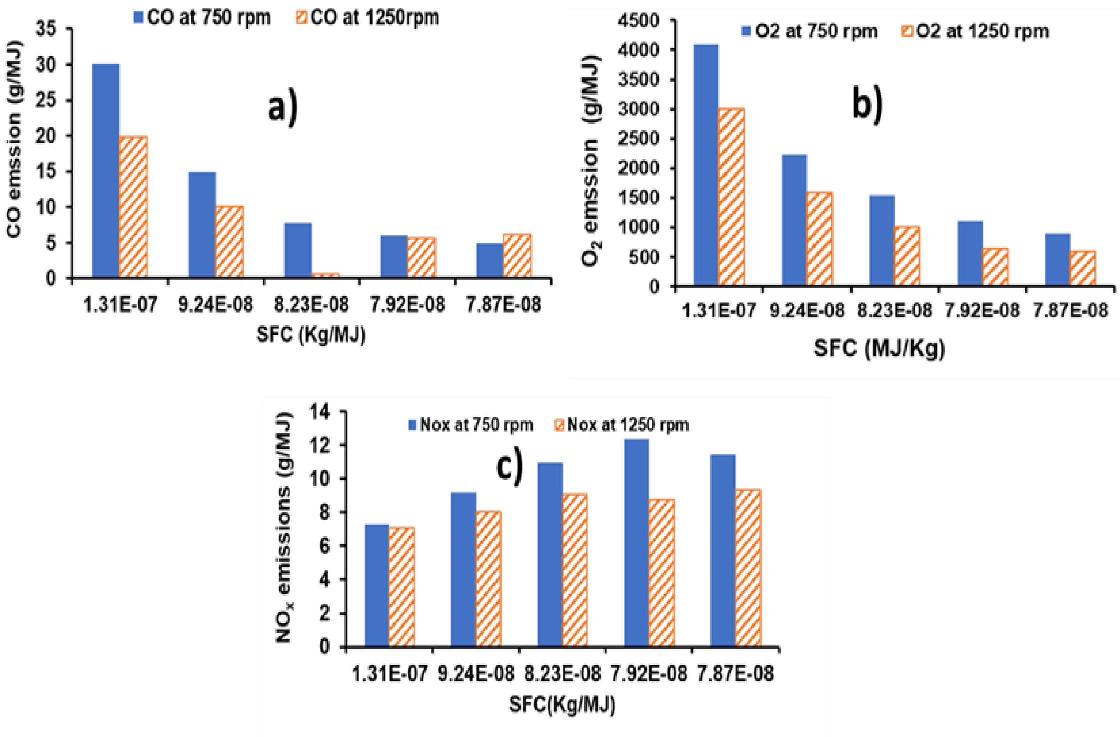

Fig.4: Variations of exhaust emissions with specific fuel consumptio (φ) a) CO b) O_2 c) NOx

Lastly, as it is available from most literatures, an ideal combustion in a CI engine should yield high bmep, faster combustion process and higher efficiency with a clean exhaust emission and less noise [15]. However, these are entirely competing requirements for an RME fuel. For instance, Dandajeh and Ahmadu [16] found that the output of the engine (bmep) increased with air-fuel ratio, equivalence ratio and exhaust gas temperatures with decrease in volumetric efficiency. This decrease in bmep could lead to an increase in CO_2 and NO_x (see Fig3a & 3e) emissions but decrease in O_2, CO and HC emissions (see Figs.3b, 3c and 3d) at both 750 rpm and 1250 rpm operating speeds. To support this, Horn *et al.* [17] reported that high distillation curve gradient of RME is responsible for its CO and HC emissions. It is also worth noting that HC production is being triggered by incomplete combustion as a result of vaporization of RME and at lower distillation temperature. Moreover, NO_x emissions could be reduced by emulsifying the RME fuel due to dissociation and consequent evaporation of water which decreases the maximum temperature [18]. Therefore, it is quite imperative to increase the bmep of this engine by turbocharging [19]. As with the case of high exhaust temperatures, this practically means much work will be extracted by the turbines at the exhaust.

4. CONCLUSION

An experimental investigation on the exhaust emissions of rapeseed methyl Esther (RME) and fossil diesel in a gardener Compression Ignition Engine was presented. The Gardener engine has a compression ratio of 14:1 and a maximum speed of 1500rpm. Experiments were carried out at two engine speeds, an intermediate low-speed of 750rpm and intermediate high-speed of 1250 rpm. The engine was operated under five loads (4, 8, 12, 16 and 18 kg) and under lean equivalence ratios ($0.2 \leq \varphi \leq 0.8$). The following conclusions were drawn.

i) Emissions of NO_x and CO_2 increased while those of HC, O_2 and CO decreased with increasing equivalence ratio, exhaust temperature (Tex), brake mean effective pressure (bmep) and specific fuel consumption (SFC).

ii) Values of all the exhaust emissions (NO_x, CO_2, HC, O_2 and CO) were found to decrease with increasing engine speed from 750 to 1250 rpm.

iii) RME was observed having lower exhaust emissions than fossil diesel at the engine speed of 750rpm and at all the loads tested.

iv) Emission reduction of RME over fossil diesel was achieved by 0.06% for O_2, 84% for CO and 4.7% for CO_2 at 750rpm. At higher speed of 1250rpm however, RME was observed having higher NOx and CO_2 but relatively lower O_2 and CO than the fossil diesel.

v) The implication of these observations is that RME can be a better substitute for a fossil diesel in a CI engine especially at low speed.

5. ACKNOWLEDGEMENTS

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