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Assessing combustion and emission performance of direct use of SVO in a diesel engine by oxygen enrichment of intake air method

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Abstract

This work investigated the effect of the oxygen enrichment in the intake air of diesel engines on the combustion and emissions performance using Rape Seed Oil (RSO) as a fuel. The purpose of the paper is to investigate the potential of oxygen enrichment in the intake air method to restrain the deterioration of particulate emissions of the RSO due to its high viscosity so as to explore the possibility of direct use of SVO (Straight Vegetable Oil) in diesel engines, which can reduce CO_2 emissions and save cost. The combustion parameters such as ignition delay, heat release rate, in-cylinder peak temperature and pressure were determined. Engine out particulate and gaseous emissions of the RSO were measured at oxygen concentrations from 21% (by volume) (no enrichment) to 24% (by volume) and compared to diesel results. The enrichment of the intake air with oxygen decreased the ignition delay and premixed combustion duration, and increased the in-cylinder peak pressure and temperature. The particulate, CO and hydrocarbon emissions were significantly reduced while the NOx emissions increased as the oxygen enrichment rate increased. 22% oxygen enrichment rate was suggested to achieve lower than diesel particulate emissions with the lowest NOx penalty. Increased NOx could be controlled by other methods. The results show that the oxygen enrichment in intake air method enabled direct combustion of SVO in diesel engines with reduced particulate, hydrocarbon and CO emissions.

Key words

Biofuel, Straight vegetable oil, Exhaust emission, Diesel engine, Oxygen enrichment

1. INTRODUCTION

Increasing environmental concerns and security of energy supply have accelerated the research and development of alternative fuels for transport and power generation applications. Biodiesel, as a most popular biofuel in transport, is made from transesterification of vegetable oils or animal fats. The transesterification process consumes the energy and produces CO_2 and increases the cost as well as rejects about 10% of the feedstock as waste glycerine. Straight vegetable oils (SVO) and waste vegetable oils or waste cooking oils (WVO or WCO) can be used as fuels in diesel engines with a better carbon footprint compared to FAME (Fatty Acid Methyl Ester). The use of waste cooking oils and SVOs is potentially cheaper than using petroleum diesel or edible oil biodiesel [1]. However, performance problems have been reported [2, 3]. These unprocessed (non-esterified) biofuels are not commonly used due to their high viscosity and low volatility, leading to poor atomisation and thus high particulate emissions as well as other problems such as handling problems and engine deposits and injector coking [4]. This study has investigated the impact of oxygen enrichment in the air inlet of the engine on the combustion and emissions characteristics of rape seed oil burned in a diesel engine. The aim is to explore the possibility of using oxygen enrichment method to overcome the adverse effect on engines and environment caused by the high viscosity of SVO so as to provide essential information to enable further evaluation of oxygen enrichment method as a way to utilise SVO (including waste cooking oils) directly in diesel engines without causing adverse impact. The primary potential application is aimed at stationary applications such as power generation.

The concept of the oxygen enrichment of intake air as a mean of improving combustion and reducing emissions in diesel engines has been investigated for a long time [5-14]. These researches focused on the air intake enrichment of conventional petroleum diesel and compared with addition of oxygenates in the petroleum diesel. Enrichment of the air intake of naturally aspirated diesel engines can be an effective measure to reduce emission and improve thermal efficiency. Previous publications on the subject suggest that the amount of O_2 addition is a trade off between NOx increase and reduction of PM (Particulate Matter), HC, CO and smoke emissions. Watson and Rigby [5] conducted experiments on a Caterpillar V-8 engine with oxygen enrichment up to 30 % (volume fraction and so as hereinafter). They found smoke emissions to decrease gradually with O_2 increase to around 10 H.S.U. (Hartridge Smoke Unit) at all engine speeds compared to 80 H.S.U. for 21% O_2 (no oxygen enrichment). NOx emissions gradually increased with increasing oxygen enrichment to about 20% at 30% oxygen, acceptable levels were found at 24 % oxygen. Particulate emissions were reduced up to 80 % at full load conditions. Desai and Watson [7] further investigated impact of different grades of diesel fuels at various O_2 enrichment rates for emission characteristics and performance. They found that smoke and particulate emissions substantially decreased due to oxygen enrichment for all fuels. Ignition Delay was found to decline at higher oxygen levels which in combination with injection timing will maintain NOx levels within acceptable levels while large benefits in PM and smoke reduction can be achieved. Donahue and Foster [8] conducted oxygen enrichment tests on a Cummins N 14 single cylinder diesel engine with oxygen rates of 21, 22 and 23 %. They found an increase to 22 % oxygen showed drastic reductions of particulate matter emissions while only moderately increasing NOx, the exact magnitude depending on injection timing. A further increase to 23 % only showed marginal decrease in PM but large unfavourable increase in NOx. Increased O_2 intake was found to reduce ignition delay and increase peak cylinder pressure for all load conditions. The increase in NOx with higher O_2 rates was attributed to increased temperatures and the PM reduction to increased fuel pyrolysis and soot oxidation. Rakopoulos et al [10] did an extensive literature review on previous research of the subject. Their conclusions are consistent with above mentioned findings; the shorter ignition delay was attributed to the accelerated pre-ignition reactions. Poola and Sekar [14] investigated the impact of oxygen enrichment of combustion air on the operational and emissions properties using a locomotive research diesel engine (two cylinder, EMD 567B). They found that the NOx could be reduced simultaneously along with PM emissions when the concentration of intake air oxygen, fuelling rate, and injection timing were optimized. Their results showed that particulates were reduced by approximately 60% and NOx emissions were reduced by 15–20% with the optimal operating strategy. Higher gross power, lower peak cylinder pressures, and lower brake specific fuel consumption were also observed. A recent study by Perez and Boehman [15] studied the effect of air inlet oxygen enrichment on engine performance at simulated high altitude conditions using a small aero diesel engine. One of their key findings was that the oxygen enrichment decreased brake-specific fuel consumption (BSFC) by 40% due to increased fuel conversion efficiency. The emission was not measured as it was not the objectives of the research. Table 1 below summarized the key elements of major publications related to experimental results of oxygen enrichment of air intake for diesel engines. Besides the experimental work, there are some theoretical researches on air intake oxygen enrichment. Zannis et al [16, 17] modelled the effect of air intake oxygen enrichment method on combustion and emissions and found similar results such as the shorter ignition delay, higher in-cylinder pressure, lower PM and higher NOx emissions with oxygen enrichment.

Table 1. Review of previous key O_2 enrichment in air intake experiments on diesels

Author and year of publication	**O_2-Enrichment Rates**	**Recommended Rate**	**Conclusions**
Watson and Rigby;1990 [5]	21-30	24	NOx control difficult but possible by retarded injection. Large reductions in PM and smoke possible.
Virk et al;1993 [6]	21-27	22.5	NOx levels were kept at the same value as the unenriched-air, while particulates and smoke emissions were reduced by 30%.
Desai and Watson;1997 [7]	21, 25, 27	25	NOx levels acceptable by injection timing control for low smoke and PM
Donahue and Foster; 2000 [8]	21, 22, 23	22	22 % only small NOx increase but large PM. 23 % only small decrease in PM but large increase in PM.
Poola and Sekar; 2003 [14]	21,23,25,27	23	At optimum oxygen-enrichment rate (~23%) and injection timing, PM emissions were reduced by ~60%, NOx emissions were reduced by ~14%, gross power was increased by ~16%, and BSFC was reduced by ~2% Such wide benefits demonstrate the potential of the oxygen-enrichment technique.
Perez and Boehman; 2009$^{\sim}$ 2010 [12] [15]	21, 22, 23	22-23	A modest decrease in BSFC by oxygen enrichment. PM emissions were reduced while NOx deterioration was minimized when combined with EGR.

2. EXPERIMENTAL

2.1 Test engine and fuels

A Perkins Phaser 180Ti 6 cylinder, 6 L (0.006 m^3), DI (Direct Injection), turbo-charged inter-cooled, heavy duty diesel engine was used, fitted with an oxidation catalyst. The specifications of the engine are shown in Table 2. The engine was of Euro 2 emissions standards compliance. The engine was running at 47kW (50% of its maximum load at this speed) and 157 rad s^{-1} constant conditions.

Table 2. Engine specifications

Type	**Perkins Phaser 180Ti**
Displacement (L)	6.0
Cylinder No.	6
Compression ratio	17.5 : 1
Maximum power rating	134kW at 272 rad s^{-1}
Aspiration	Turbo-charged and Inter-cooled
EGR	No
Fuel injection	Pump-line-nozzle
Injector hole diameter, (mm)	0.2
The number of holes	6
Injection timing, ^{O}BTDC	11
BMEP at 47kW & 157 rad s^{-1} (KPa)	628

A food grade virgin Rapeseed Oil (RSO), Agri green extended life cooking oil and produced by Agri Energy Food Service co, was used as the testing fuel. The oil was produced by deep degumming process and the key fuels properties were listed in table 3.

Table 3. Selected physical properties of the test fuel RSO

Properties	**Values**
Colour	15Yellow

	/1.5 red
Free fatty acids (mass fraction %) max	0.15
Protein (mass fraction %)	0
Insoluble impurities	
(mass fraction %) max	0
Density @15^{o}C (kg m^{-3})	922
Kinematic viscosity @40^{o}C (mm^{2} s^{-1})	35.61
Flash point (^{o}C)	320
Oxygen (mass fraction %)	17.5
Calorific value (MJ kg^{-1})	39

2.3 Oxygen enrichment layout

The oxygen was supplied by four 46.6 L (0.0466 m^{3}) capacity cylinders, passing through a pressure regulator and a volumetric flow meter and transported to a valve. The oxygen was then passed through a mass flow meter with an accuracy of 1%, which was connected to a laptop for the control and measurement of oxygen flow rate. The influence of surrounding temperatures on the oxygen flow rate was minimal as all the pipes and meters were housed indoors and the temperature was maintained at 15±2°C. The metered oxygen was injected into the air stream by inserting a probe downstream of the intercooler and one meter upstream of air inlet manifold of the engine. A dedicated sample probe was inserted in the engine air inlet manifold and connected to a Servomex paramagnetic oxygen analyser to measure the oxygen concentration after mixing with an accuracy of ±0.1% of oxygen concentration. The readings were used to monitor oxygen level and adjust oxygen flow rate if necessary. Figure 1 shows the schematic view of the experimental set up.

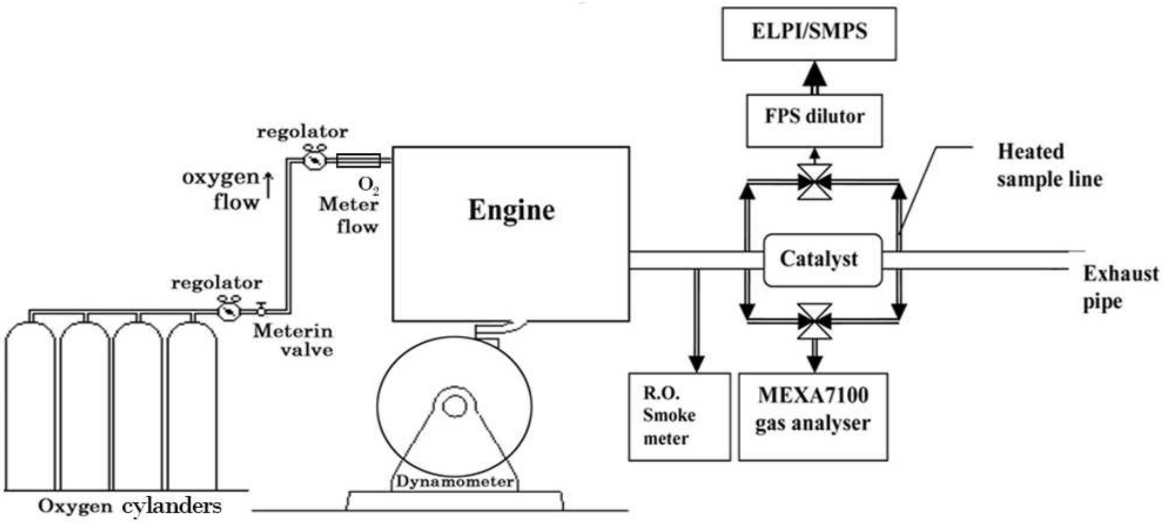

Figure 1. Schematic view of oxygen enrichment test set up

2.4 In-cylinder pressure and crank angle measurement

One of the cylinders on the test engine was fitted with a piezo-electric pressure transducer for measuring in-cylinder pressure, which was connected to a data acquisition system that could take around 100, 000 pressure readings per second. The Top Dead Centre (TDC) position was measured using an optical sensor and indentation on the flywheel at TDC. The time based pressure results were then converted into P-θ (pressure-crank angle) diagram. At least 50 cycles were converted for each condition. An average P-θ diagram was then obtained. The heat release rate was thus calculated. The ignition delay and premixed combustion duration (PCD) was then determined. The variations were determined and indicated by the error bars (absolute error) in the figure 7. This method has also been used by other researchers [18-20] and proved to be reliable. The ignition delay was defined as from the beginning of fuel injection at 11 ° BTDC (Before Top Dead Centre) until the start of premixed combustion. The PCD was defined between the end of ignition delay and the start of stratified combustion. The in-cylinder peak temperature was computed based on peak pressure data.

2.5 Emissions sampling systems

The particulate and gaseous exhaust samples were taken at 1.3 m from the turbocharger upstream of the catalyst and at 2.05 m downstream of the catalyst respectively, as shown in figure 1. A constant temperature sampling (CTS) technique was used with a 6.3 mm (0.0063 m) stainless steel pipe inserted with a curved bend onto the centre line of the exhaust pipe. The sample for particulate collection was passed through a heated sample line to a heated filter in an oven at 50°C. The SAE smoke meter (R.O.smoke meter manufactured by Richard Oliver Ltd.) was used, which was modified to include separate temperature control of the filter paper block and the oven. There was sufficient sample residence in the oven to cool the sample to 50°C. Whatman 0.055 m diameter GF/F glass fibre filters were used with a 0.029 m spot size. The sampling flow rate was kept at 5 L min^{-1} and at least 0.001 g of particulate was collected, weighed to 0.000010 g resolutions and hence the minimum accuracy of the filter weights was ±2%.

Gas samples were taken from the same sample position in the exhaust as the particulates and transported via a 6 m long 6.3 mm diameter electrically heated Teflon tube to a Horiba MEXA-7100D on-line gas analysis system. The sample line temperature was kept at 190°C. The exhaust gas analysis system contained a heated FID (Flame Ionization Detector) analyzer for total hydrocarbon analysis, a Chemiluminescence analyzer for NO and NO_2 analysis, and two NDIR (Non-Dispersive Infrared) analyzers for CO and CO_2 analysis. The air/fuel ratio was calculated from the gas analysis results based on the carbon balance principle, taking into account the oxygen content of the biofuels. This was used to convert the measured emissions data from volumetric to mass emissions. The exhaust gas samples were measured every 5 seconds and at least 300 readings were taken on each testing condition.

3. RESULTS AND DISCUSSION

3. 1 Fuel viscosity

One of the major problems for using RSO in diesel engines is its much high viscosity compared to diesel fuel. The kinematic viscosity of the RSO was measured as a function of temperature along with the standard diesel fuel as shown in figure 2. The RSO had a much higher viscosity than the diesel fuel and its viscosity was much more variable with temperature. It was observed during the experiment that the temperature of the RSO was raised from room temperature in the fuel tank to ~55 ^{o}C before entering the fuel injector due to the pumping heat and the heat from the engine block. However, the difference in viscosity between the RSO and diesel at the fuel injection point was still significant. The high viscosity of the RSO would deteriorate the fuel spray and atomization and affect mixing of fuel with air and therefore adversely affect combustion and emissions [21]. The cone angle of fuel spray decreases, and the size and penetration of fuel droplets increase as the viscosity of fuels increases. This could cause direct contact of fuels with the combustion chamber wall, the piston surface and rings, resulting in carbon deposits formation. The high viscosity could also lead to higher pressure accumulations in the fuel injectors and fuel lines and cause early fuel injections. Another adverse effect of the high viscosity of the RSO is the dilution of the engine lubricating oil.

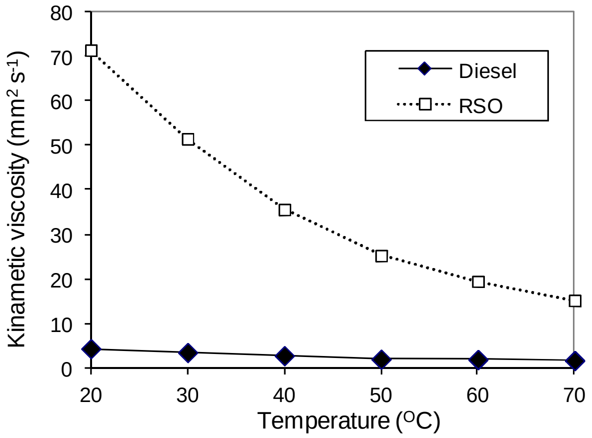

Figure 2. Fuels kinematic viscosity as a function of temperature

3.2 Combustion parameters - ignition delay, premixed combustion, peak in-cylinder pressure and temperature, heat release and indicated efficiency

Figure 3 shows the pressure-crank angle (p-θ) diagram of the RSO at four different oxygen enrichment rates/levels. The fuel was injected at 11^o BTDC. The ignition occurred at approximately 5^o ATDC. The results show a clear trend towards shorter ignition delays as the oxygen rate increased. The peak pressure was increased from ~6.8 MPa to 7.2 MPa, ~6% increase, as the oxygen rate increased from 21% to 24%. Figure 4 shows computed in-cylinder gas temperatures for different oxygen rates using the equation of state for ideal gas. Obviously, this was the mean gas temperatures inside the cylinder. Though the emissions in diesel engine combustion are dominated by local temperature but the mean in-cylinder temperature is strongly connected with the local temperature in the IC engines. The peak temperature was increased from ~1780 to ~1950 K when the oxygen rate was increased from 21% to 24%, about 9% increase. Compared to diesel, the RSO showed the lower in-cylinder pressure at the TDC. This could be due to two reasons. The first possible reason is that the typical value of the specific heat capacity of rape seed oil is 1.91 kJ $kg^{-1}K^{-1}$ while diesel is 1.8 kJ $kg^{-1}K^{-1}$. The higher specific heat of RSO leads to more heat absorption and heat transfer from hot air to the RSO. The second possible reason is due to the advance of fuel injection. Several researches have reported an inadvertent advance in fuel-injection timing using biodiesel. It is caused by a higher bulk modulus comparing to diesel fuel [22-24]. The second peak of in-cylinder pressure is higher for diesel fuel (compared to 21% oxygen RSO) because the ignition delay of RSO is longer (fuel injection and evaporation of RSO takes more time) than diesel. The higher pressure by oxygen enrichment for the RSO at around 370~375 ^{o} crank angle showed more intensive diffusion combustion, reflected by the higher peak in-cylinder temperature. Figure 5 shows the peak in-cylinder temperature as a function of oxygen enrichment rate for the RSO. A good linear correlation is observed.

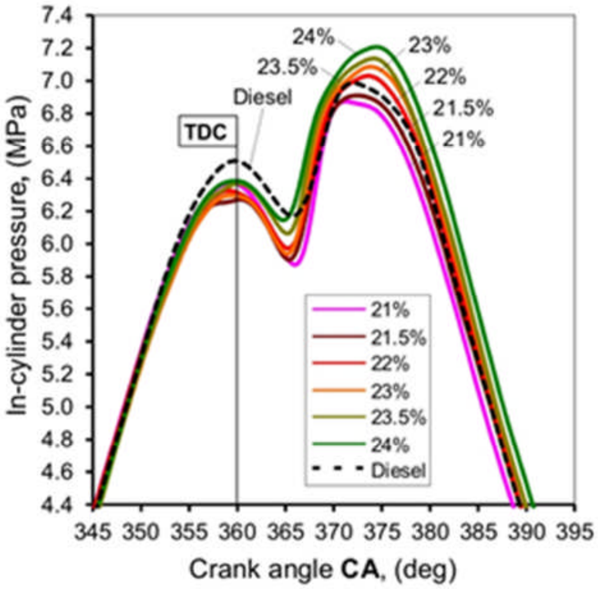

Figure 3. In-cylinder pressure variation as a function of crank angle (CA) for different oxygen rates

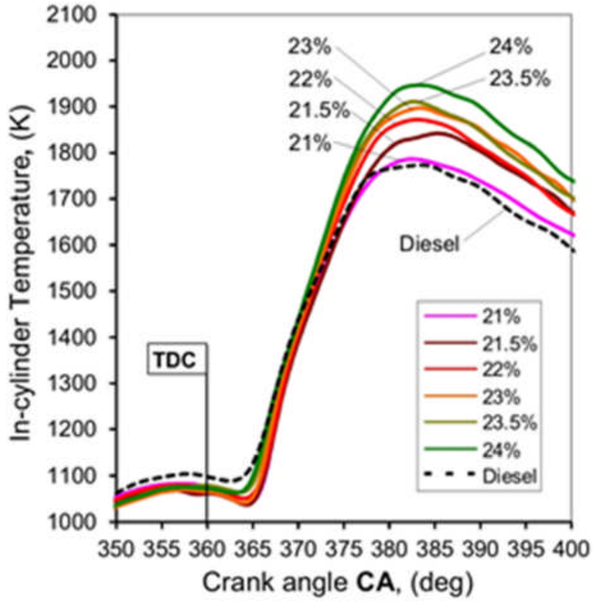

Figure 4. In-cylinder temperature variation as a function of crank angle (CA) for different oxygen rates

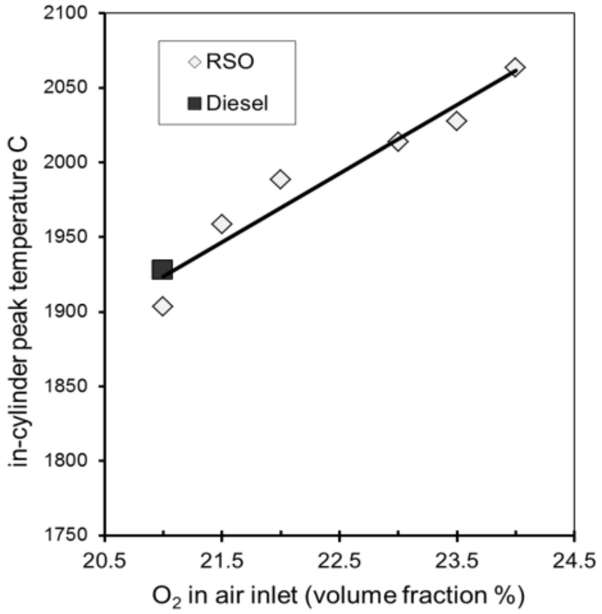

Figure 5. In-cylinder peak temperature as a function of oxygen rate

Figure 6 shows the heat release rate for different oxygen rates. The negative values before ignition reflected the heat absorption by the RSO due to its evaporation, which was ~5 J deg^{-}

[1]. The results show that the peak heat release rate was reduced as the oxygen rate increased. This was due to that the shorter ignition delay at the higher oxygen rates reduced the fractions of fuels burned in the premixed combustion phase. In contrast to the reduction of premixed combustion phase, the diffusion combustion phase was extended at the higher oxygen rates, along with a higher diffusion peak heat release (the second heat release peak) as shown in figure 6. It was the higher heat release rate in the diffusion phase that caused higher mean in-cylinder peak temperatures in figure 4, which then resulted in higher NOx emissions.

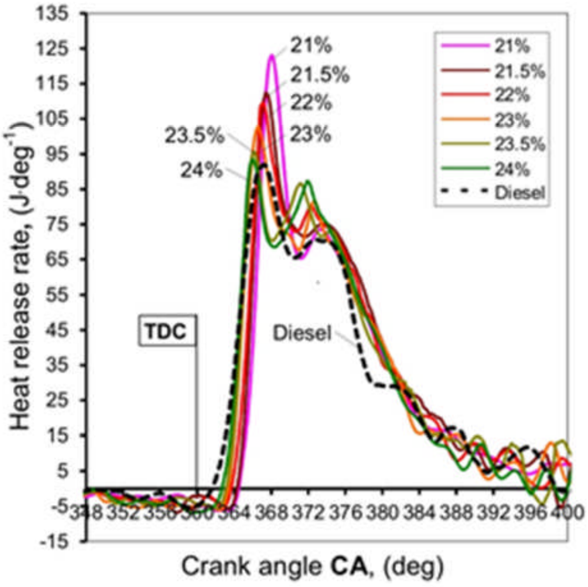

Figure 6. Heat release traces for different oxygen rates

The trend of ignition delay and PCD was plotted against the oxygen rates with error bars as shown in figure 7. The error bars indicated the absolute error of the measurements. Both the ignition delay and PCD show a significant decrease with increasing oxygen rates. The reduction of the ignition delay was 1.7 ° at 24 % oxygen compared to oxygen level of 21%. The shorter ignition delay resulted in shorter PCDs and longer diffusion combustion periods and thus higher flame temperatures and consequently higher NOx. The oxygen enrichment caused the air fuel mixture during the PCD to be leaner, supporting higher NOx formation through higher local temperatures in the PCD and, hence, in the NOx-forming diffusion flame. The CO and hydrocarbon formation was reduced as a result of higher in-cylinder temperatures and the air fuel ratio being leaner and further away from stoichiometric with the increased oxygen rate. The additional oxygen could also result in late cycle oxidation of CO and hydrocarbons further reducing these emissions. The ignition delay was gradually reduced because the air fuel mixture will ignite at a lower temperature with more oxygen present. Compared to diesel's ignition delay with the RSO without oxygen enrichment in figure 7, it shows that the RSO had approximately 20% longer ignition delay than the diesel. This is related to a lower cetane number of the RSO (~20% lower). Another possible reason is due to the slower evaporation of the RSO. The results in figure 7 also show that the diesel had a longer premixed combustion phase. This is due to that the amount of diesel injected during the ignition delay period was greater than the viscous RSO. In other words, the low cetane number of the RSO extended its ignition delay and the high viscosity of the RSO shortened its premixed combustion period due to less amount of fuel being injected.

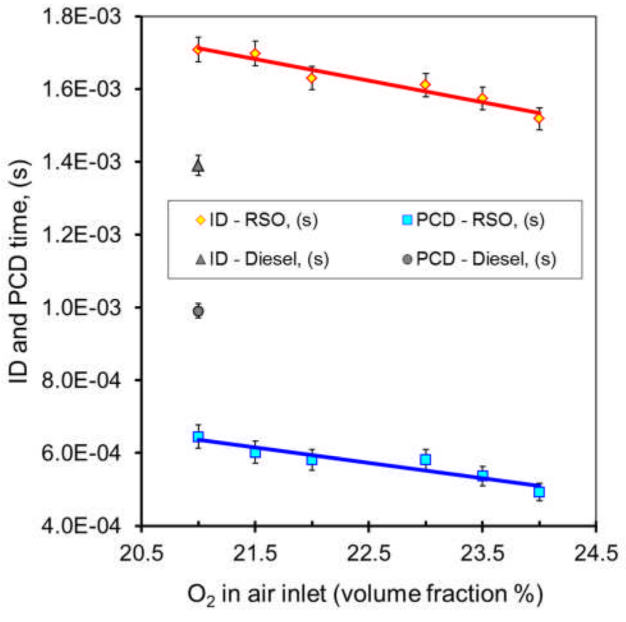

Figure 7. Changes in ID and PCD for different oxygen rates

Figure 8 shows the indicated engine efficiency as a function of oxygen rate. As expected, oxygen enrichment increased indicated engine efficiency. The maximum improvement of indicated efficiency is about 0.6% at 24% oxygen rate, which could be translated to about 1.2 % fuel saving due to improved combustion efficiency by oxygen enrichment.

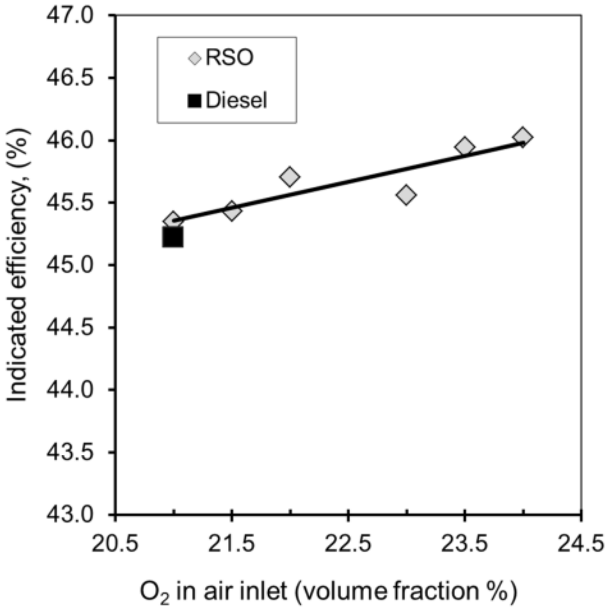

Figure 8. Indicated efficiency as a function of oxygen rate

3.3 Exhaust emissions

3.3.1. Particulate emissions

The particulate matter (PM) was collected on the filter papers and mass emissions were determined. Figure 9 shows the particulate specific emissions (g kWh^{-1}) as a function of oxygen rate. The PM specific emissions from the standard diesel were also plotted as a reference. Compared to diesel, RSO PM emissions (without oxygen enrichment) were increased by ~30% due to its high viscosity and low volatility. The oxygen enrichment could effectively reduce the PM emissions from RSO. In fact, PM emissions from oxygen enrichment rate of 22% onwards were significantly lower than that of diesel fuel. The reductions in the PM mass of the RSO were the most significant between 21% and 22% of oxygen levels and became much slower afterwards. The higher in-cylinder gas temperature and extra oxygen helped the oxidation of the soot, resulting in less PM emissions. The EU emission regulation for EURO 2 heavy duty diesel after 1998 production is 0.15 g kWh^{-1}, which is based on ECE R-49 test cycle with 13 steady state modes. The direct comparison of this research results with the EU regulation is not appropriate but the results in figure 9 could give an indication of PM emission levels relative to the regulation on a particular mode, i.e.50% of load at low speed mode, which was the operation condition of the test in this research.

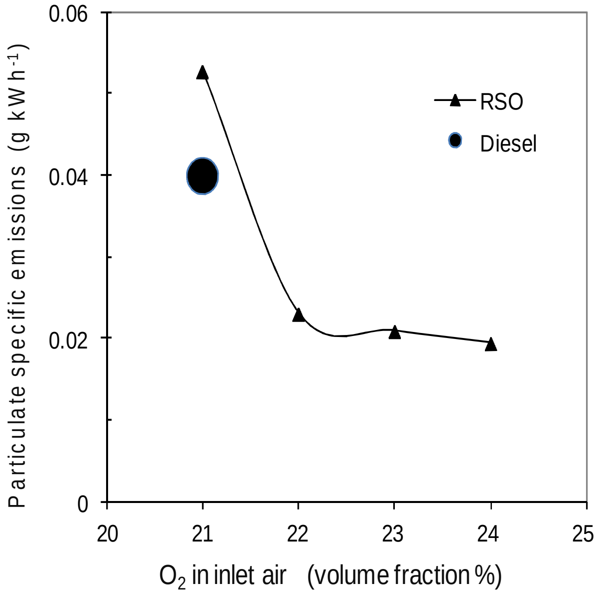

Figure 9. PM specific emissions as a function of oxygen rate

3.3.2. Nitrogen oxides (NOx) emissions

The EU NOx emission standard for this type of engine is 7 g kWh^{-1} based on ECE R-49 cycle. The condition the engine was tested represented one of the ECE R-49 mode, 50% of maximum power at low engine speed. The NOx level (6 g kWh^{-1}) from the diesel fuel was already close to the standard. Figures 10 and 11 show the specific NOx emissions as a function of oxygen rate and peak in-cylinder temperature respectively. As expected, the NOx emissions increased significantly as the oxygen enrichment rate rose due to three major NOx formation contributors: the higher flame temperature, the higher local oxygen concentration and the longer diffusion combustion phase. A good linear correlation between NOx emissions and oxygen rate was observed. The NOx emissions were almost trebled to 17 g kWh^{-1} at the highest oxygen rate (24%). The adverse effect on the NOx by oxygen enrichment could be minimised or even eliminated by changing fuel injection strategy - late fuel injection and adjusting fuel injection rate, as illustrated by Poola and Sekar [14]. The NOx could also be reduced by the use of EGR. Essentially, EGR and oxygen enrichment in intake air are two opposite methods serving two different purposes. The former is for NOx reduction while the latter is for PM reduction. A common practice is the combination of EGR with the other oxygen enrichment methods such as oxygenated fuels. However, these are out of the scope of this research. The NOx could also be treated with exhaust aftertreatment technologies such as SCR (Selective Catalytic Reduction) using urea. But a cost/benefit analysis is needed to assess the benefit of particulate reduction and penalty of NOx increase and associated cost of aftertreament.

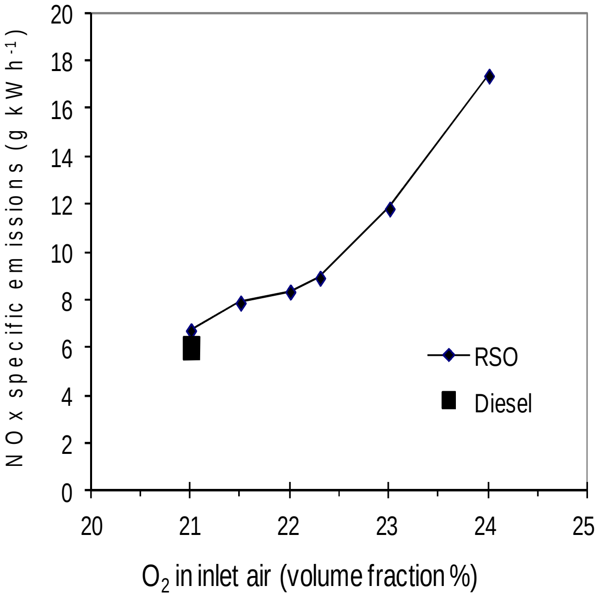

Figure 10. NOx specific emissions as a function of oxygen rate

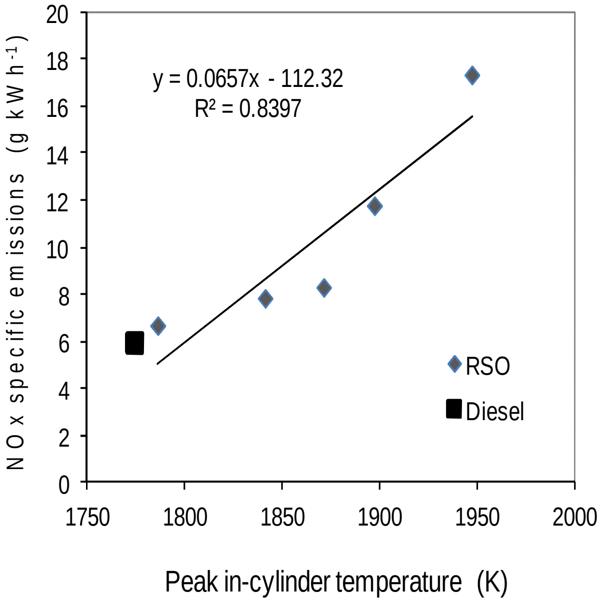

Figure 11. NOx specific emissions as a function of peak in-cylinder temperature

3.3.3. CO and THC emissions

The total hydrocarbon (THC) and CO specific emissions are presented in figure 12 as a function of oxygen rate, along with the reference data of diesel results. Both the THC and CO emissions are clearly showing strong tendencies of reductions as the oxygen enrichment increased due to the oxidation effect taking place with additional oxygen. By comparison of CO emissions between the diesel and the RSO at 21% oxygen level, it was suggested that the poor atomization and mixing of the RSO occurred, indicated by much higher CO emissions from the RSO. Surprisingly, there was no deterioration of hydrocarbon emissions from the RSO compared to diesel. This could be attributed to the fuel born oxygen in the RSO assisted the oxidation of the fuel.

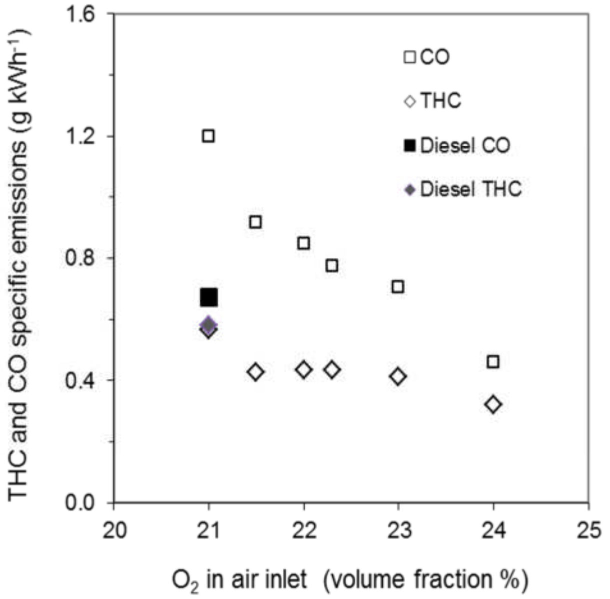

Figure 12. Specific emissions of THC and CO as a function of oxygen rate

3.4 Normalised emissions.

The PM and gaseous specific emissions were normalised to the values at oxygen concentration of 21% (no oxygen enrichment) and presented in figures 13-15 in order to show the relative changes of emissions as a function of oxygen enrichment rate. The PM had a large decrease at oxygen concentration 22%, a reduction of ~60% compared to no oxygen enrichment. The reductions were much slower afterwards to an almost flat level.

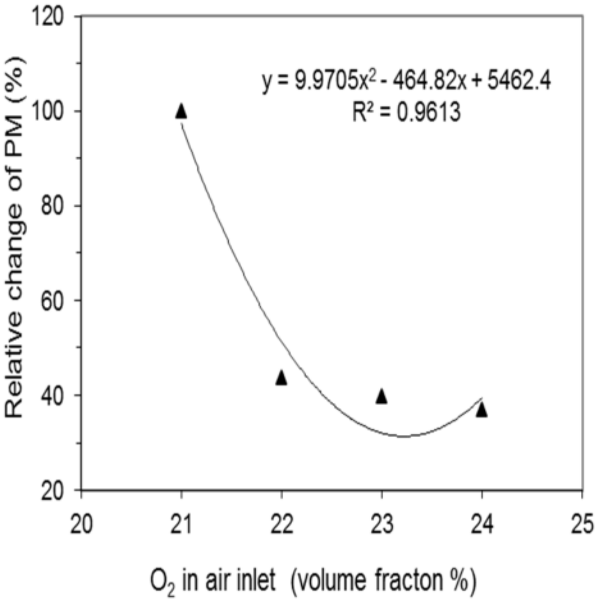

Figure 13. Normalised particulate specific emissions as a function of oxygen rate

The normalised NOx specific emissions in figure 14 demonstrated a very good positive linear correlation with oxygen enrichment rate. The NOx emissions were increased by 150% at oxygen concentration of 24%, an average increase of ~50% for every 1% of increment of oxygen enrichment.

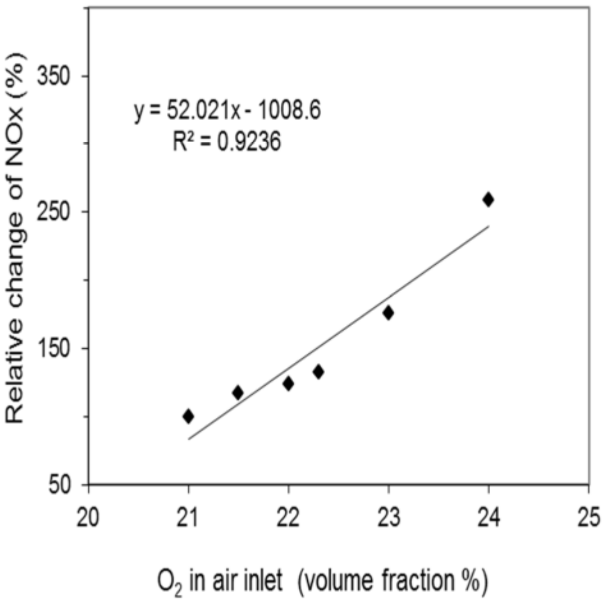

Figure 14. Normalised NOx specific emissions as a function of oxygen rate

Both the THC and CO specific emissions showed negative correlations with oxygen enrichment rate. The CO emissions showed a better linear correlation than the THC emissions. The CO and THC emissions were reduced by approximately 20% and 15% per 1% oxygen enrichment rate respectively.

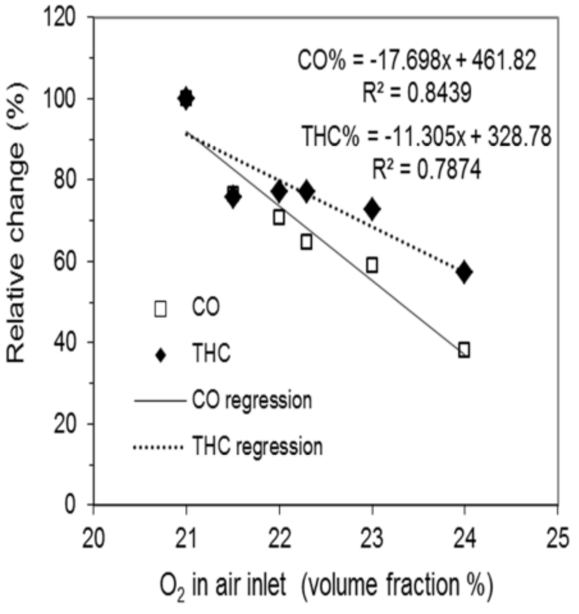

Figure 15. Normalised THC and CO specific emissions as a function of oxygen rate

4. CONCLUSION

Direct use of pure SVO as a fuel in diesel engines without transesterification can offer greater CO_2 savings and lower cost compared to conventional biodiesels (FAME). However, high viscosity, low volatility of SVOs could lead to deteriorated combustion and emissions. The oxygen enrichment in the air inlet of the engine method as a way to improve the SVO's combustion so as to reduce emissions was investigated in this work. The air inlet oxygen levels tested were from 21% (no enrichment) to 24%. The results show:

1. The oxygen enrichment in the engine air inlet resulted in the shorter ignition delay and premixed combustion duration and longer diffusion combustion phase. The shorter ignition delay reduced the peak heat release rate at the premixed combustion phase but increased the peak heat release rate at the diffusion combustion phase. Overall the in-cylinder peak pressure and temperature were increased by 6% and 9% respectively when the oxygen rate was increased from 21% to 24%. This resulted in an improvement in engine efficiency measured by indicated efficiency.

2. Without oxygen enrichment, the RSO produced ~30% higher particulate emissions than the diesel at the same engine operating condition. However, the particulate emissions could be reduced to below the diesel level with oxygen enrichment rate of 22%. The reductions in particulate emissions were not linear with the oxygen enrichment rate. There was a large reduction in particulate emissions (~60%) between 21% (no enrichment) and 22% of oxygen level. The reductions were in a much less scale with the further oxygen enrichment.

3. NOx emissions showed a good positive linear correlation with oxygen enrichment rates and were increased on average by 50% for every 1% of oxygen enrichment rate. The high in-cylinder temperature and pressure are accounted for the higher engine out NOx emissions.

4. Without oxygen enrichment, the significantly higher CO emissions of the RSO, compared to diesel, indicated a poor atomisation and mixing of the RSO with air. The oxygen enrichment could reduce the CO emissions to a compatible level to diesel. The fuel born oxygen in the RSO helped the RSO to produce similar levels of hydrocarbon emissions to diesel. The oxygen enrichment overall reduced engine out CO and THC emissions.

5. The optimised oxygen enrichment rate should be 21~22%, where a significant reduction in particulate can be achieved with the lowest increase in NOx emissions.

6. The findings from this work demonstrated that adverse effects (deteriorated combustion and high emissions) of direct use of SVO in diesel engines can be solved and overcome by the oxygen enrichment method. This enables industrial diesel applications such as electric power generations to use the pure SVO directly to achieve greater CO_2 reductions and reduced fuel cost compared to biodiesel.

NOTES

The authors declare no competing financial interest.

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NOMENCLATURE

ATDC: After Top Dead Centre

BSFC: Brake Specific Fuel Consumption

BTDC: Before Top Dead Centre
CO: Carbon Monoxide
DI: Direct Injection
EGR: Exhaust Gas Recirculation
FAME (Fatty Acid Methyl Ester)
H.S.U.: Hartridge Smoke Unit
NOx: Nitrogen Oxides
PCD: Premixed Combustion Duration
PM: Particulate Matter
RSO: Rape Seed Oil
SCR: Selective Catalytic Reduction
SVO: Straight Vegetable oil
TDC: Top Dead Centre
THC: Total Hydrocarbon

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