THE INFLUENCE OF AIR SIDE AND FUEL SIDE WATER ADDITION ON ENGINE'S BEHAVIOUR OF A BIOFUEL BASED COMPRESION IGNITION ENGINE UNDER OXYGEN ENRICHED COMBUSTION

by

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The effect of water injection at the air side and water addition at fuel side on engine's performance of a Diesel engine was studied under oxygen enriched intake air using neat mahua oil as fuel. Initially experiments were carried out using neat mahua oil as fuel with different oxygen concentrations such as 21% (ambient), 22.4%, 23.8%, and 24.7% by volume at the air side. The optimal oxygen concentration was found based on the engine's brake thermal efficiency. At the optimal oxygen concentration water injection was done on air side at 4% by mass and the experiments were repeated with neat mahua oil as fuel under oxygen enrichment mode. Finally, mahua oil emulsion was prepared using the same amount of water (i. e. 4%) and tested in the engine. A comparative study was made for the same amount of water (i. e. 4% as optimal) for water injection and neat mahua oil emulsion on engines behavior. Oxygen enrichment increased the brake thermal efficiency with all concentrations and reached the maximum value from 25.2% with ambient oxygen to a maximum of 30.6% at 23.8% of oxygen enrichment at the maximum brake mean effective pressure of 5.4 bar whereas it was 30.8% with neat diesel. The smoke, HC, and CO emissions were significantly reduced with oxygen enrichment. However, oxygen enrichment increased the NO emissions at all concentrations. Injection of water and emulsification techniques reduced the NO emissions considerably. Emulsification showed more reduction in NO emission than water injection for the same amount of water. It was concluded from the study that neat mahua oil could be effective used as fuel in compression ignition engines by combusting it under oxygen enriched condition. The optimal oxygen concentration of 23.8% could be recommended for the highest brake thermal efficiency. Injection of water at the intake manifold and emulsification techniques could solve the problem of higher NO emissions. The optimal amount of water that could be injected without affecting the engines power and brake thermal efficiency could be recommended as 4% by volume. Emulsification has the added advantage of further improvement in engine's brake thermal efficiency.

Key words: *Diesel engine, mahua oil, oxygen enrichment, water injection, emulsification, engine performance, emission, combustion*

Introduction

Vegetable oils are promising alternative fuels for compression ignition (CI) engines as they are easily available, renewable and most of the properties are very close to diesel

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Table 1. Properties of fuels

Properties	Neat diesel	Neat mahua oil (NMO)
Density, [kgm^{-3}]	850	960
Low heating value, [kJkg^{-1}]	42490	36000
Viscosity (cSt) at 40 °C	4.59	24.6
Flash point, [°C]	68	232
Pour point, [°C]	15	–20
Water content, [%]	1.6	0.02
Ash content, [%]	0.9	0.01
Carbon residue, [%]	3.7	0.17
Cetane number	45	46
Auto ignition temperature, [°C]	260	300

[1-3]. Among the available vegetable oils, mahua oil (MO) appears to be a very promising fuel for Diesel engines due to its non-edible nature and easy availability (particularly in south India). The important properties of mahua oil are found to be very close to conventional diesel as seen in tab. 1. Past studies reported that mahua oil could be used as fuel directly in Diesel engines [3-5]. However, its poor volatility, high viscosity and density make it difficult to burn completely in Diesel engines. Oxygen enrichment in the intake air is considered as one of the effective methods in reducing smoke and particulate emissions in Diesel engines when using vegetable oils as fuels. It is a simple method which needs no modification in either engine side or in fuel side [6-8]. Oxygen enriched combustion in Diesel engines was attempted by a number of researchers in the past using diesel and vegetable oils as fuels and reported that oxygen enrichment technique could be adopted for reducing smoke, HC and CO emissions of Diesel engines fuelled with vegetable oils as fuel [7-9]. However, past studies reported that the emissions of NO_x were significantly high with oxygen enrichment technique with diesel and vegetable oils as fuels in Diesel engines due to the excess oxygen present in the combustion chamber and the attainment of high temperature of the products of combustion [8, 9].

Use of emulsified fuel indicates as an effective method of controlling NO emissions in Diesel engines. It requires the fuel to be modified to its emulsion by using an emulsifier called as surfactant. Investigations made to study the effect of oxygen enrichment in intake air on combustion of Diesel engines using water diesel emulsions reported significant reduction in smoke emissions and NO emissions as well [10-12]. It has been reported that with the increase of water emulsion ratio the reduction in smoke and NO to be more significant. Introducing a small amount of water along with the intake air looks as another and easy way of controlling NO emissions without modifying either in engine side or fuel side. Earlier studies presented good reduction in NO emissions using diesel as fuel in Diesel engines with intake manifold water injection (WI) technique [13-15].

It looks from previous studies that oxygen enrichment at the intake of the engine is helpful in controlling smoke emissions in Diesel engines with improved brake thermal efficiency (BTE). Since the main problem of vegetable oil as fuel in Diesel engine is very high smoke emissions, providing additional oxygen can help in complete combustion of the injected vegetable oil. Injection of a small amount of water along with the incoming air finds an easy way of reducing the cycle temperature. Combining WI along with oxygen enrichment could achieve simultaneous reduction of smoke and NO emissions with vegetable oil as fuel without modifying the engine or fuel. Use of emulsified fuels could also achieve simultaneous reduction of NO and smoke emissions in Diesel engines without modifying the engine. In addition it has the benefit of superior BTE than neat fuel. In view of the above an attempt was made to burn mahua oil in a single cylinder agricultural Diesel engine under oxygen enriched condition. In the first phase of work engine was operated using diesel and NMO as fuel for providing baseline data with the oxygen concentration intake air as 21%. In the second phase of work oxygen concentration was varied from 22% to 25% at the increment of 1% and the engine was tested with NMO as fuel. In the third phase WI was also made in steps of 1%, 2%, 3%, and 4% by volume at the engine's intake. From the trials the amount of WI was fixed as 4% in order to maintain the BTE. The same amount of water was used for preparing the emulsion of MO and the prepared emulsion was tested as fuel in the final phase. Engine performance, emission and combustion parameters were obtained for all the trials and analyzed at different brake mean effective pressure (BMEP) with the fixed engine speed of 1500 rpm.

Engine experimental set-up and experiments conducted

The test engine used for the study is a single cylinder, four-stroke water-cooled, direct injection, agricultural Diesel engine. The complete engine specifications are presented in tab. 2. The detailed information about the engine experimental set-up and the instruments used can be seen in fig. 1 and tab. 3.

Table 2. Engine specifications

Make	Kirloskar -AV 1
General details	Four-stroke, CI, water-cooled, NA, single cylinder engine
Bore and stroke	85 mm × 110 mm
Compression ratio	16:1
Rated power output	3.7 kW at 1500 rpm
Injector opening pressure	200 bar
Displacement volume	630 cc
Connecting rod length	165.3 mm
Combustion chamber	Open, hemi spherical piston
Injection system	Individual pump with mechanical injector
Fuel injection timing	27° bTDC (NMO) 25° bTDC neat diesel

A separate oxygen intake system was developed for enriching the oxygen admitted inside the cylinder. The oxygen gas (with 97% purity) was compressed and stored at 150 bar in the special container, allowed to come out at 2 bar and passed through the gas flow meter. The WI was made by using a solenoid operated injector controlled by a separate electronic control system. A 12 V electric pump was used to supply the water at a pressure of 3 bar. The MO emulsion was prepared by mixing 4% of water (by mass) with 94% of NMO in the presence of 2% of surfactant called as span 80. Before conducting all the trials, the injection timing was optimized for neat diesel, NMO, and MO emulsion based on the maximum BTE. The injection timings were varied from 21 °CA to 29 °CA in steps of 2 °CA intervals. The optimal injection timings were found as 25 °CA for neat diesel and 27 °CA for NMO and its emulsion. Hence during the entire investigation the injection timing was set at 27° bTDC as optimum timing for NMO and its emulsion and 25° bTDC for neat diesel. Engine trials were made at the rated speed of 1500 rpm with the variable power outputs (such as 40%, 60%, 80%, and 100% power outputs). Readings for engine speed, torque, exhaust gas temperature (EGT), and fuel-flow rate were recorded for obtaining performance parameters. Smoke opacity, HC, CO, and NO emissions were measured using the emission analyzers for emission analysis. In cylinder pressure and TDC signals were acquired and stored by a high-speed (AVL Indismart Gigabit) computer based digital data acquisition system. The combustion analyzer had a 14-bit analog to digital converter to convert analog signals to digital form. The analog to digital (AD)

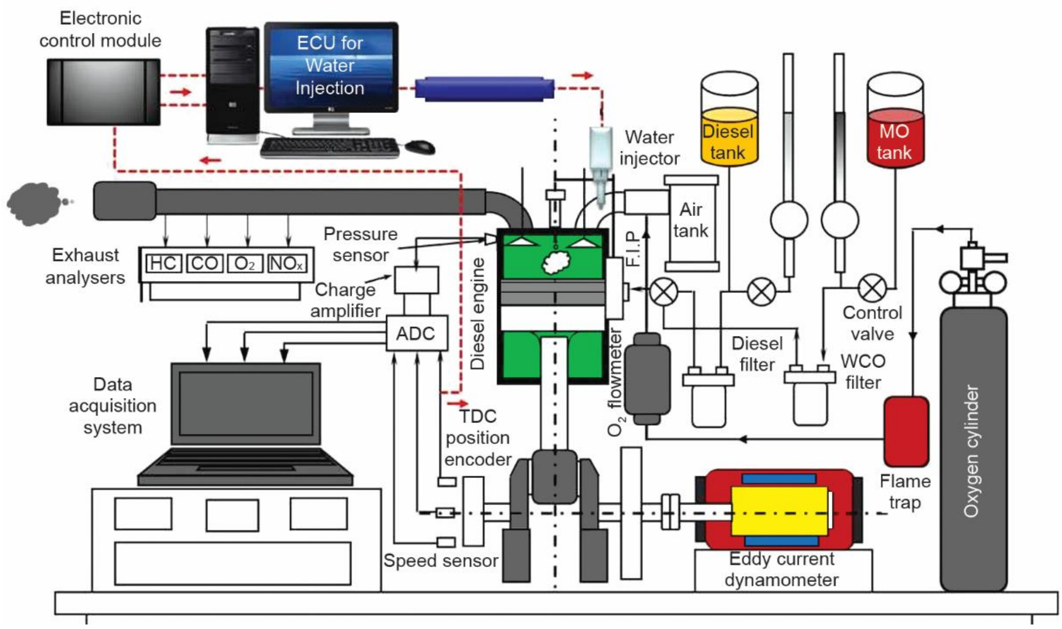

Figure 1. Test engine set-up with oxygen enrichment and WI systems

Table 3. Details of instruments used and their uncertainty details

Parameter	Instrument used	Measuring range	Accuracy	Percentage uncertainty
Brake power [kW]	Eddy current dynamometer (BENZ SYSTEMS)	0-50	± 0.5	±1%
Fuel flow rate [gcc^{-1}]	Burette and stop watch	0-200	0.5	±2%
CO [%]	AVL Digas 444 five gas analyzer	0-10	±0.03	±0.8
HC [ppm]	AVL Digas 444 five gas analyzer	0-20000	±10	±0.9
NO [ppm]	AVL Digas 444 five gas analyzer	0-5000	±10	±1
Smoke opacity [%]	AVL 437 C smoke meter	0-100	±1	±1

converter had external and internal triggering facility with sixteen single ended channels. A Kistler made air cooled piezoelectric pressure sensor was used for measuring in cylinder pressure. Cylinder pressure data from 100 consecutive cycles were recorded by the data acquisition system and the signals were averaged for one cycle and processed by the specially developed AVL software to obtain combustion parameters like peak pressure, maximum rate of pressure rise, heat release rate, *etc.*

Results and discussion

Engine performance characteristics

The variation of BTE with NMO as fuel under oxygen enriched combustion for different loads (BMEP) can be seen in fig. 2. It is seen that NMO resulted in lower BTE as compared to neat diesel at all loads. At peak load it was noted as 25.4% with NMO and 32.4% with neat diesel. However, there is an improvement in BTE with oxygen enrichment technique at all enriched amounts of oxygen as seen in fig. 2. It increased to a maximum of 28.3%, 30.7%, and 27.2% for the oxygen concentrations of 22.7%, 23.8%, and 24.7% respectively (by volume) at the maximum BMEP.

The improvement in BTE with oxygen enrichment can be explained by the complete combustion of the NMO due to the availability of more oxygen in the combustion chamber. Similar result of increased BTE has been observed by many researchers in the past and reported by the improvement in combustion efficiency of the fuel due to more availability of oxygen [16-18]. It could be seen from the fig. 3 that the calculated air fuel equivalent ratio, λ, showed clear increment with NMO as fuel at all BMEP with excess oxygen was present in the combustion chamber when oxygen enrichment was made at all levels such as 22.4%, 23.8%, and 24.7% during the intake process.

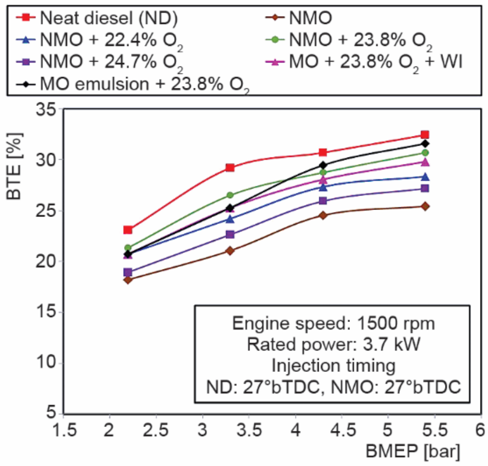

Figure 2. Variation of BTE with BMEP

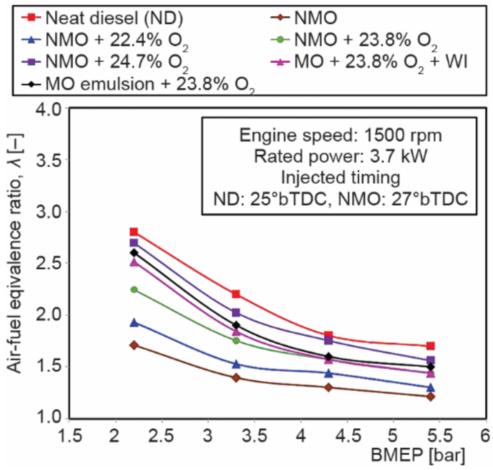

Figure 3. Variation of air fuel equivalence ratio, λ, with BMEP

Looking at the fig. 4 that the peak cycle temperature calculated from the pressure volume data became higher with all amounts of oxygen enrichments as compared to the ambient air intake at all BMEP which indicated the combustion process to be superior as compared to NMO operation at ambient air condition. It was noted that beyond 23.8% the BTE dropped due to the very high temperature of the charge and more heat transfer. Hence it was decided to fix the optimal oxygen concentration for best BTE as 23.8% by volume. The WI showed a small drop in BTE at all BMEP. This can be explained by the presence of water in the combustion chamber which reduced the charge temperature and the peak cycle temperature as indicated in fig. 4. However the values of BTE were found to be still higher than neat NMO operation. At peak load BMEP the BTE was noted as 29.8% with WI. It is interesting to see that using NMO in the form of its emulsion resulted in the BTE of 31.5% at 100% load which is very close to diesel value. The increased BTE with the MO emulsion could be explained by the presence of water in the emulsion which resulted in secondary atomization of the fuel (called as micro-explosion) and resulted in complete combustion and rapid energy release. However at part loads emulsified MO showed slightly inferior performance due to the low temperature of the charge as a result of the low temperature of the combustion chamber parts.

The EGT shown in fig. 5 is very high with neat NMO at all BMEP as compared to neat diesel. At peak BMEP the EGT was noted as 478 °C with NMO whereas it was 345 °C for neat diesel operation. The increase in EGT with NMO can be explained by the poor combustion of the NMO which resulted in prolonged combustion during the later stages of combustion. However oxygen enrichment considerably reduced the EGT at all BMEP due to the complete combustion of the NMO under oxygen enriched condition.

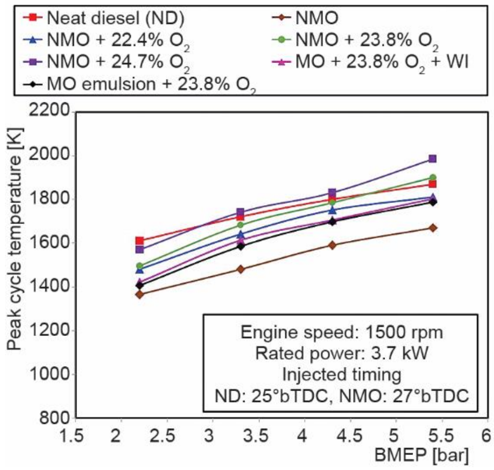

Figure 4. Variation of peak cycle temperature with BMEP

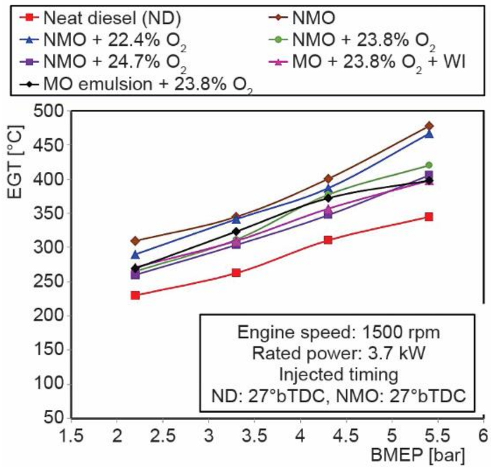

Figure 5. Variation of EGT with BMEP

It can be seen from the integral heat release diagram (which will be discussed in the fig. 12) that the total heat released was more with oxygen enrichment as compared to the engine operation without oxygen enrichment when using NMO as fuel. The EGT was noted as 421 °C with the oxygen enrichment of 23.8% at the peak BMEP. The WI and emulsification techniques further reduced the EGT at all BMEP due to charge cooling as a result of vaporization of water.

Engine emission characteristics

The variation of smoke emission with NMO under ambient and oxygen enriched operation at different loading conditions can be seen in fig. 6. Smoke emission increased with NMO at all BMEP as compared to neat diesel. At peak power output (*i. e.* BMEP) the smoke emission was noted as 67% and 40% with NMO and neat diesel, respectively. Considerable reduction in smoke emission can be seen with oxygen enrichment technique with NMO as fuel at all BMEP at all concentrations of oxygen.

The smoke value was reduced to a minimum of 58%, 48%, and 45% with NMO for the oxygen concentration of 22.4%, 23.8%, and 24.7%, respectively, at the intake charge at maximum power output. The main reason for the reduction in smoke emission with the oxygen enrichment is due to the enhanced mixture preparation which reduced the local fuel rich regions present in the combustion chamber. Due to the excess oxygen combustion was complete and hence the smoke emission was reduced. However, WI slightly increased the smoke emission at all BMEP as compared to the results without WI. This trend can be explained by the combustion process affected by the presence of water in the combustion chamber. The low temperature of the charge (due to the presence of water) caused the combustion to be incomplete and resulted in smoke emission to be more. It is very interesting to see that when the fuel was converted into its emulsion and used as fuel there was a drastic reduction in smoke emission at all BMEP. The main reason for the reduction in smoke emission with the emulsified MO is due the main process occurring in the engine called as the secondary atomization of the injected droplet fuel [13]. It has been reported that during fuel injection into the very high temperature air, heat transfer occurred between the air and the droplet and the droplets are heated up. When the mean temperature of the fuel droplet was increased above the boiling point of water, the water quickly and violently evaporates, breaking the droplet into smaller droplets, which results in a more complete vaporization and turbulent mixing of the fuel. The smoke emission was noted as 46% with MO emulsion at 100% load (*i. e.* at the maximum BMEP).

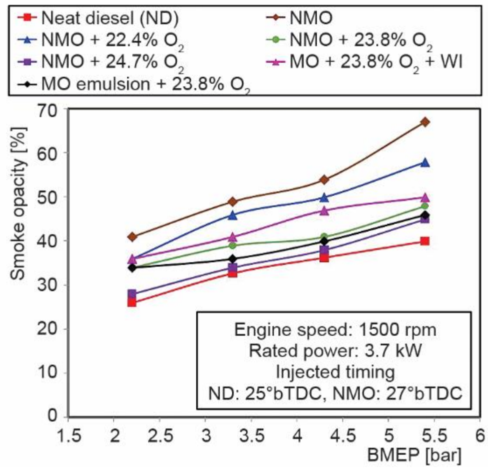

Figure 6. Variation of smoke opacity with BMEP

The variation of HC emission can be seen in fig. 7 for different approaches using NMO as base fuel. At the maximum BMEP the HC emission was found as 75 ppm with neat diesel and 99 ppm with NMO. The main reason for the higher HC with NMO operation is due to the result of incomplete combustion of NMO. The high viscosity and poor volatility of NMO resulted in slow combustion and increased the HC emissions. Considerable reduction in HC emission was observed at all BMEP with oxygen enrichment technique using NMO as fuel at all levels of oxygen concentration.

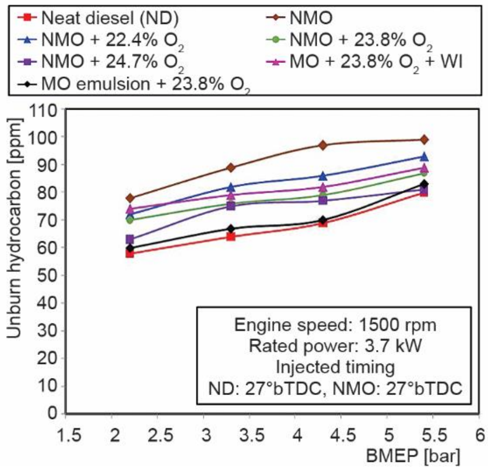

Figure 7. Variation of unburn HC with BMEP

At the peak BMEP the HC emission was noted as 93 ppm, 87 ppm, and 81 ppm with 22.4%, 23.8%, and 24.7%, respectively, of oxygen enrichment at the intake air. Improved oxidization due to the availability of oxygen and high in cylinder temperature were found to be responsible for the result of lower HC emission with oxygen enrichment. However, WI raised the HC emission. At peak power the value was found as 89 ppm. It is seen from fig. 5 that MO emulsion resulted in lower HC emissions of the methods tried. The values were found to very close to diesel values at all BMEP. AT the maximum BMEP the HC emission was noted as 83 ppm. Improved vaporization and atomization of the NMO emulsion as a result of micro explosion may have helped in better mixing of the fuel with air and resulted in complete combustion of the fuel.

The variation of CO emission with different approaches can be seen in fig. 8. The NMO at ambient oxygen condition resulted in considerable raise in CO emission as compared to neat diesel at all BMEP. At the maximum BMEP the value was noted as 0.23% with NMO whereas it was 0.12% with neat diesel. The fuel richness caused by the low energy content of the NMO of could be the reason for the increase in CO. With oxygen enrichment there was a considerable reduction in CO emission at all BMEP with NMO.

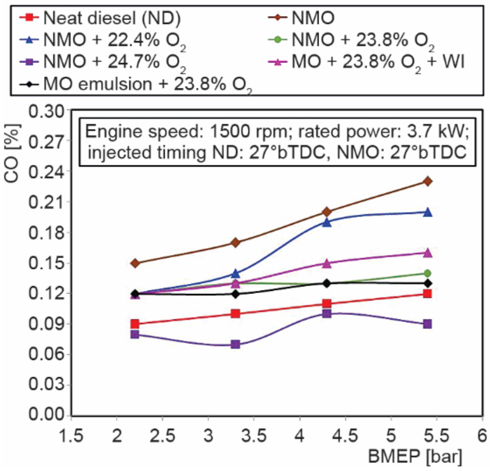

Figure 8. Variation of CO with BMEP

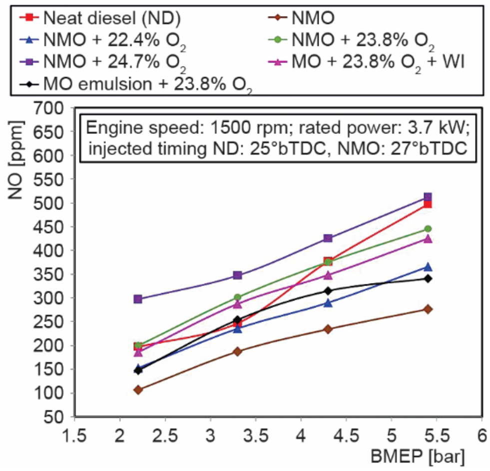

Figure 9. Variation of NO with BMEP

It reduced to a minimum of 0.2%, 0.14%, and 0.09% with 22.4%, 23.8%, and 24.7% oxygen concentrations, respectively, in the air intake at the maximum BMEP. The reduction in CO emission with oxygen enrichment could be very well explained by the availability of oxygen in the combustion chamber which helped in complete oxidation of the carbon in the fuels. However, WI resulted in slight increase in CO emission at all BMEP (0.16% at peak power). This raise could be realized by the low temperature of the combustion chamber charge which affected the combustion process to completely oxidize the carbon atoms of the fuel to CO_2. It is interesting to see that emulsified MO resulted in reduced CO emissions as compared to WI and noted as 0.13% at the maximum BMEP as seen in fig. 8.

Figure 9 shows the effect of oxygen enrichment, WI and emulsification techniques on NO emission of the engine fuelled with NMO. The NMO resulted in lower NO emissions at all BMEP as compared to neat diesel under ambient oxygen concentration in the intake air. The values were noted as 276 ppm and 497 ppm respectively with NMO and neat diesel at peak BMEP. However, oxygen enrichment with MO resulted in increased NO emissions at all BMEP with all enriched concentrations of oxygen. At 100% load the NO emission was observed as 445 ppm with NMO at 23.8% of oxygen enrichment. The increase in NO emission in the exhaust can be explained very well by the increase in bulk cycle temperature immediately after combustion. However, WI and emulsification techniques resulted in reduced NO emission at all BMEP. The NO reduced to a minimum of 365 ppm with 4% WI and 341 ppm with emulsion of NMO at the maximum BMEP of 5.4 bar. This trend can be explained by the presence of water inside the combustion chamber which reduced the peak cycle temperature due to its vaporization. Hence, WI and emulsification techniques are highly beneficial in controlling NO emissions.

Engine combustion characteristics

The variation of cylinder pressure histories with different approaches can be seen in fig. 10 for the maximum BMEP condition. The cylinder pressure traces of NMO indicated similar to that of neat diesel with lower peak value than neat diesel as seen in fig. 10.

There is a considerable rise in cylinder peak pressure with oxygen enrichment with all enriched amounts of oxygen. The maximum pressure increased from 54.8 bar with NMO operation to a maximum of 55.2 bar, 61.5 bar, and 58.6 bar, respectively, with 22.7%, 23.8%, and 24.7% oxygen concentrations at peak BMEP. The maximum pressure was noted as 64.5 bar with neat diesel. The increase in cylinder pressure with oxygen enrichment could be explained by the improvement in combustion process due to the enriched oxygen in the intake charge. However WI reduced the peak pressure as 59.1 bar. It is seen that MO emulsion indicated the highest peak pressure of all the methods (63 bar) which is very close to diesel.

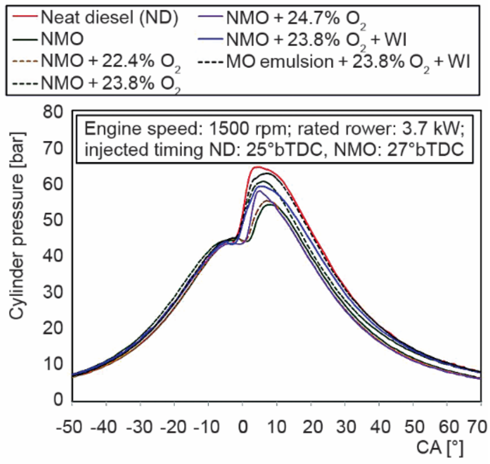

Figure 10. Variation of cylinder pressure CA diagram at peak load (BMEP)

Figure 11 presents the variation of the ignition delay with BMEP for different approaches when using NMO as the base fuel. The ignition delay was calculated from the rate of pressure rise curve derived from the cylinder pressure crank angle (CA) diagram and the needle lift signals. The start of injection was obtained from the needle lift sensor and start of ignition was found from the second derivative of the pressure curve. The ignition delay shown in fig. 11 is higher with NMO as compared to neat diesel at all BMEP. It is seen that, oxygen enrichment (at all enriched concentrations) resulted in reduced ignition delay at all BMEP when using NMO as fuel. It reduced from 12 °CA with NMO (at ambient oxygen condition) to 10 °CA with 23.8% of oxygen enrichment at the maximum BMEP. The reduction in ignition delay with oxygen enrichment could be due to the ignition of the NMO to occurs even at low temperatures due to the availability of more oxygen. However, WI and emulsion of MO increased the ignition delay even with oxygen enrichment at all BMEP. It was noted as 11 °CA at the maximum BMEP with WI and emulsion of MO whereas the ignition delay was noted as 10 °CA with neat diesel.

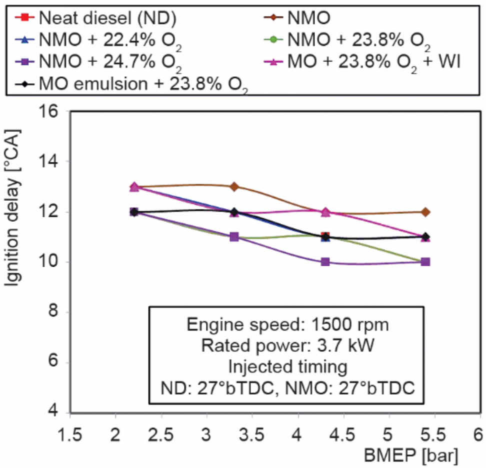

Figure 11. Variation of ignition delay with BMEP

An important and significant combustion parameter in determining the combustion efficiency of an internal combustion engine is the combustion duration. It is defined as the CA or time period between the point of start of combustion to the point of end of combustion. The start of ignition was obtained from the heat release rate curve. The CA where the positive heat release occurred was considered as the point of ignition and the point of end of combustion which was taken as the 90% of the total heat released. The total combustion duration increased with NMO as compared to neat diesel at all BMEP as seen in fig. 12. High viscosity and density of the NMO resulted in slower combustion rate and lead to late burning to be more. However, the combustion duration decreased with the oxygen enrichment technique. This is mainly due to the increase in rapid burning rate of NMO due to oxygen enrichment. The faster combustion

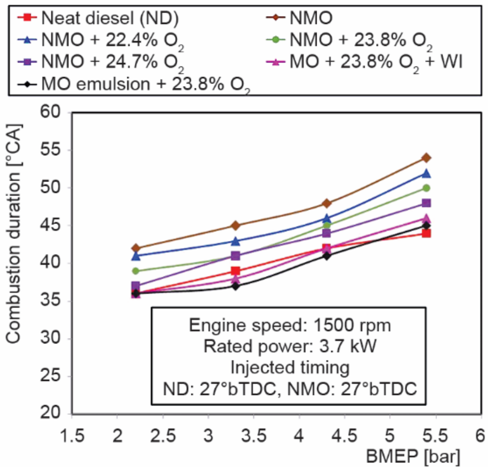

Figure 12. Variation of combustion duration with BMEP

rate in the premixed burning phase and shorter diffusive burning phase decreased the total combustion duration of the NMO under oxygen enriched combustion. The MO emulsion also indicated considerable reduction in combustion due to the fast combustion as a result of micro explosion. However, WI showed increased trend of combustion duration at all BMEP as seen in fig. 11. This could be due to the effect of charge cooling which may have extended the combustion duration.

Figure 13 shows the heat release rate variations with different modes of engine operation using NMO as base fuel. For calculating the heat release rate the first law of thermodynamics on energy conservation was used. As in thermodynamics, simplified calculation process which determines the energy effectively delivered to the gas is taken in to account using the equation:

$$Q_{\text{gross}} = \frac{\gamma}{\gamma - 1}(P\text{d}v) + \\ + \frac{1}{\gamma - 1}(v\text{d}P) + Q_{\text{w}}$$

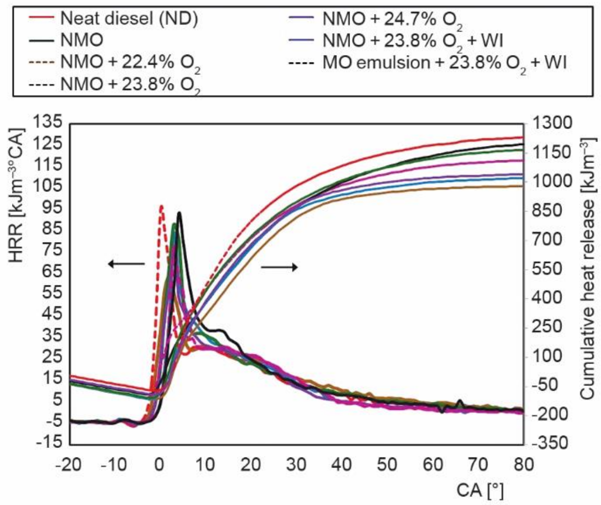

Figure 13. Variation of heat release rate with crank angle at peak load (BMEP)

where Q_{gros} is the gross heat release rate, γ – the ratio of specific heats, v [m^3] – the instantaneous volume of the cylinder, P [bar] – the cylinder pressure, and Q_{w} – the equation for wall heat transfer.

The cylinder contents were considered as homogeneous and act as ideal gas. Crevice effects were eliminated and specific heat ratio was calculated as a function of cycle temperature. The heat transfer was calculated based on Hohenberg's equation [18] and the wall temperature was assumed to be 723 K [19]. With NMO as fuel the heat release rate was noticed to be inferior in the early stage of combustion called as the premixed phase. The mixing controlled combustion was noted to be significant as seen in fig. 13. However, oxygen enrichment improved the heat release rate in the premixed combustion phase with NMO at all concentrations of oxygen. Drop in heat release rate was noted with WI due to the combustion process affected by the presence of water in the intake air. However, MO emulsion indicated improvement in heat release rate in the premixed combustion phase (even though there is a delay in start of ignition) as seen in fig. 13.

Conclusion

The influence of WI and emulsification techniques on engines performance and emissions of a NMO based Diesel engine under oxygen enriched combustion was studied experimentally. From the previous results it can be concluded that oxygen enrichment technique can be an effective method to use NMO efficiently as fuel in Diesel engines with reduced smoke, HC and CO levels at all BMEP. However, the raise in NO emission needs attention. Injecting a small amount of water at the intake manifold along with air could help in controlling NO emission without modifying the engine or fuel. The 4% of water could be preferred in order to maintain the thermal efficiency. Emulsification of the MO could arrive simultaneous and significant reduction in smoke and NO emissions. Emulsification has the added advantage of reduced HC and CO emissions as well. However, the fuel needs modification. In addition the poor part load performance of the emulsified fuel must be resolved.

Nomenclature

BMEP – brake mean effective pressure, [bar]
BTE – brake thermal efficiency, [%]
bTDC – before top dead center
CA – crank angle, [°]
MO – mahua oil
NA – naturally aspirated
MO emulsion – mahua oil emulsion
WI – water injection

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