AN EXPERIMENTAL ASSESSMENT ON THE INFLUENCE OF HIGH OCTANE FUELS ON BIOFUEL BASED DUAL FUEL ENGINE PERFORMANCE, EMISSION, AND COMBUSTION

by

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This paper presents an experimental study on the effect of different high octane fuels (such as eucalyptus oil, ethanol, and methanol) on engine's performance behaviour of a biofuel based dual fuel engine. A single cylinder Diesel engine was modified and tested under dual fuel mode of operation. Initially the engine was run using neat diesel, neat mahua oil as fuels. In the second phase, the engine was operated in dual fuel mode by using a specially designed variable jet carburettor to supply the high octane fuels. Engine trials were made at 100% and 40% loads (power outputs) with varying amounts of high octane fuels up-to the maximum possible limit. The performance and emission characteristics of the engine were obtained and analysed. Results indicated significant improvement in brake thermal efficiency simultaneous reduction in smoke and NO emissions in dual fuel operation with all the inducted fuels. At 100% load the brake thermal efficiency increased from 25.6% to a maximum of 32.3, 30.5, and 28.4%, respectively, with eucalyptus oil, ethanol, and methanol as primary fuels. Smoke was reduced drastically from 78% with neat mahua oil a minimum of 41, 48, and 53%, respectively, with eucalyptus oil, ethanol, and methanol at the maximum efficiency point. The optimal energy share for the best engine behaviour was found to be 44.6, 27.3, and 23.2%, respectively, for eucalyptus oil, ethanol, and methanol at 100% load. Among the primary fuels tested, eucalyptus oil showed the maximum brake thermal efficiency, minimum smoke and NO emissions and maximum energy replacement for the optimal operation of the engine.

Key words: *Diesel engine, mahua oil, dual fuel operation, engine performance, emissions, combustion*

Introduction

Biomass derived vegetable oils are considered as sustainable alternative fuels to conventional diesel fuel [1-4]. However, their direct use in Diesel engines results in very high smoke emissions with reduced thermal efficiency [5, 6]. Dual fuel operation finds a simple and effective way of reducing smoke and improving thermal efficiency of Diesel engines using vegetable oils as fuels [7, 8]. Dual fuel engine is a modified Diesel engine in which generally a high octane indexed gaseous fuel along with air is supplied during the intake process, compressed and ignited by firing a small amount of liquid fuel injected during the compression stroke. The injected fuel spontaneously auto ignites and initiates combustion of the in-

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ducted gaseous air mixture [9]. Diesel engines with appropriate and relatively simple conversion make the engine to accept any fuel to use efficiently in dual fuel mode. This type of engine also has the advantage of running in pure diesel-vegetable oil mode. Enormous work has been carried out on dual fuel engines using gaseous fuels such as natural gas, biogas, liquefied petroleum gas, and hydrogen as inducted primary fuels when using diesel and vegetable oil as pilot fuels [7, 8, 10, 11]. However, the information indicates that the engine with gaseous fuel supply requires sophisticated fuel flow control meters, special gas carburettor, and safety devices such as flame trap, flame arrester, gas cylinder, which make the intake system a very complex one when using gaseous primary fuels.

Liquid fuels are potential candidates to overcome the previous problem. High octane liquid fuels like ethanol and methanol look very attractive to use as primary fuels in dual fuel engines as their properties indicated in tab. 1, such as high octane number, self-ignition temperature, low viscosity, and good vaporisation characteristics. Studies on the use of alcohols in Diesel engines reported significant results on engine's performance and smoke reduction [12, 13]. Experiments conducted by Hongyuan *et al.* [14] on a six cylinder common rail Diesel engine with methanol diesel dual fuel mode reported improvement in combustion stability and fuel economy. Investigations carried out by Li *et al.* [15] on a heavy duty Diesel engine under dual fuel mode with methanol revealed improvement in combustion rate and reduced NO_x and smoke emissions. Tests performed by Boretti [16] on a heavy duty truck engine under dual fuel mode with ethanol as primary fuel indicated reduced particulate, CO_2, and NO emissions. It is evident from the past studies that dual fuel operation can be effective in reducing smoke emissions with alcohols while using diesel as pilot fuel with improved brake thermal efficiency (BTE) and heat release rates.

Mahua oil (MO) is a non-edible vegetable oil appears to be a very promising fuel for Diesel engines due to its easy availability (particularly in south India) and properties such as cetane number, calorific value, density, flame velocity, and self-ignition temperature are very close to diesel as seen in tab. 1 [17, 18]. Methanol and ethanol were recommended by most of the researchers in the past for dual fuel operation as primary liquid fuels. Eucalyptus oil is an another biomass derived liquid fuel looks very attractive to use as primary fuel for dual fuel operation due to its unique properties very close to gasoline as indicated in tab. 1. It has superior

Table 1. Properties of fuels [12, 13, 16-22]

Properties	Gasoline	Methanol	Ethanol	Eucalyptus oil	Diesel	Mahua oil
Density [kgm^{-3}]	719	790	780	895	850	960
Calorific value [kJkg^{-1}]	43900	19665	27200	43270	42490	36000
Self-ignition temperature [°C]	520	464	423	300	260	300
Viscosity at 40 °C [cSt]	0.4	0.65	1.52	2	4.59	24.6
Cetane number	2	3	10	25	45	46
Octane number	80	88	110	90	–	–
Flash point [°C]	–42	11	10	54	68	232
Heat of vaporization [kJkg^{-1}]	350	1100	838	305	256	–
Flame velocity [cms^{-1}]	33	40	38.5	40	40	30

energy content as compared to other biomass derived HC fuels [19, 20]. Though a number of studies have been carried out on dual fuel Diesel engines using various liquid and gaseous fuels, information indicated no engine analysis on using MO dual fuel operation with alcohols as fuel supplement for enhancing engine's performance behaviour. In addition detailed analysis on combustion behaviour of a dual fuel engine with MO as pilot fuel with alcohols (methanol and ethanol) and eucalyptus oil as primary fuels was not studied in detail.

In view of the previously mentioned it was decided to use methanol, ethanol, and eucalyptus oil as primary fuels for dual fuel operation for improving the engine behaviour of the MO based Diesel engine. The influence of eucalyptus oil, ethanol, and methanol induction on performance emission and combustion characteristics of a MO based dual fuel engine was studied experimentally. In the first phase of the work, the engine was operated on neat diesel (ND) and neat mahua oil (NMO) at two different loads such as 40% (part load) and 100% load (peak load) for baseline data generation. In the second phase the engine intake system was modified to supply primary fuels (eucalyptus oil, ethanol, and methanol) by incorporating a vaporizer arrangement. A modified carburettor system was used to supply varying amount of primary fuels along with air by fumigation technique. The amount of fuel delivered was varied by adjusting the jet opening path. Experiments were carried out using MO as pilot fuel with eucalyptus oil, ethanol, and methanol being used as primary fuels at 100% and 40% loading conditions. The amount of primary fuel induction was varied from 0% to the maximum possible energy limits where knock or misfire occurs. Engine performance and emission parameters were obtained and analysed.

Engine set-up and experiments conducted

The experimental study was conducted on a single cylinder, water cooled, Diesel engine developing a power output of 3.7 kW at 1500 rpm. The test engine had a displacement volume of 630 cm^3 and the compression ratio was 16:1. The fuel injector opening pressure was set as 200 bar. The schematic view of the engine set-up can be seen in fig. 1.

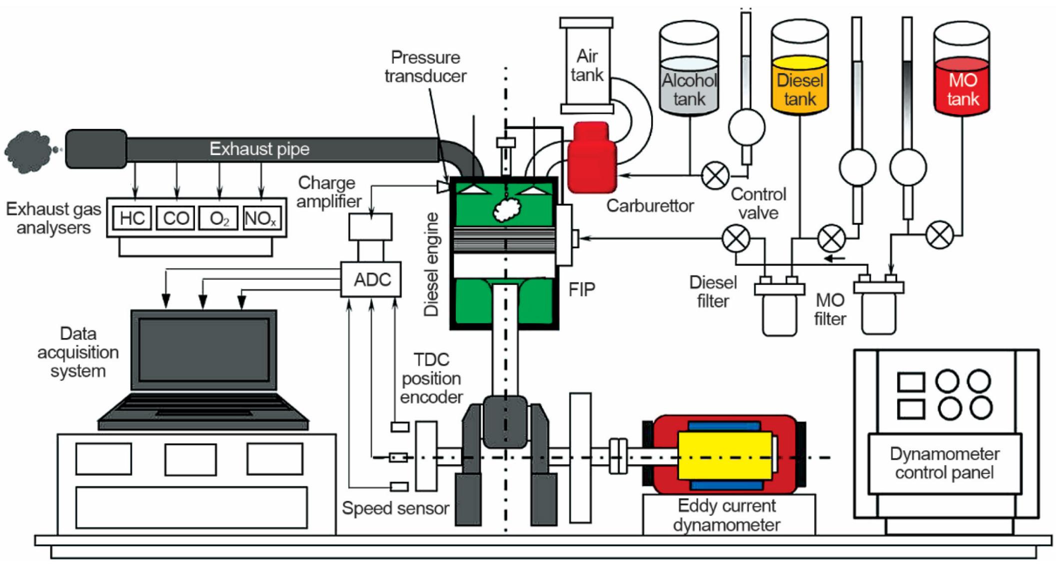

Figure 1. Engine set-up
ADC – analog to digital converter, FIP – fuel injection pump, TDC – top dead center

The engine load control was regulated by an eddy current dynamometer (BENZ SYSTEMS) coupled directly with the engine and the engine speed was fixed by varying the fuel injection. The fuel flow measurement was made on the volumetric basis. An AVL NDIR exhaust analyser was used for measuring HC, CO, and NO in the exhaust. The HC and NO emissions were measured in terms of ppm and CO emission was measured in % by volume as standard units. Black carbon smoke levels were obtained by using a standard AVL smoke meter. The details of the instruments used for the experiments and their uncertainty can be seen in tab. 2.

Table 2. Details of instruments used and their uncertainty details

S. No.	Parameter	Instrument used	Measuring range	Accuracy	Percentage uncertainty
1	Brake power [kW]	Eddy current dynamometer (BENZ SYSTEMS)	0-50 kW	±0.5 kW	±1% kW
2	Fuel flow rate [gcc^{-1}]	Burette and stop watch	0-200 g	0.5 g	±2% g/sec
3	In-cylinder pressure	AVL indismart with Kistler pressure sensor	0-100 bar	±0.1 bar	±1.2% bar
4	CO [%]	AVL Digas 444 five gas analyser	0-10% vol.	±0.03%	±0.8%
5	HC [ppm]	AVL Digas 444 five gas analyser	0-20000 ppm [vol.]	±10 ppm	±0.9% ppm
6	NO_x [ppm]	AVL Digas 444 five gas analyser	0-5000 ppm [vol.]	±10 ppm	±1% ppm
7	Smoke opacity [%]	AVL 437 C Smoke meter	0-100%	±1%	±1%

The engine was initially run with ND and NMO as fuels in single fuel mode of operation. Dual fuel operation was achieved by inducting the primary fuels along with air during the suction stroke of the engine by using a variable jet carburettor fitted at the intake manifold of the engine. The amount of primary fuel admission was varied by using a needle screw and the jet. The primary air-fuel mixture was ignited by injecting the MO (as pilot fuel) in the conventional way by the injection system. Engine trials were initially made to optimise the injection timing for the all the methods adopted. The injection timing was varied from 21 to 29 ° bTDC with 2° crank angle (CA) intervals for each method. The engine's BTE was considered for the optimisation criteria. The injection timing with maximum BTE was selected as the optimal injection timing. From the experiments the fuel injection timing was optimised and set as 25° bTDC for single fuel operation and 27° bTDC for dual fuel operation with MO. The optimal injection timing for diesel was 23° bTDC. At each load (*i. e.*100% and 40%) the primary fuel admission was varied from 0 to the maximum possible limit until the engine knocks or misfire. Readings for engine speed, torque, exhaust gas temperature, and fuel flow were recorded for obtaining performance parameters. Emissions were obtained from analysers for each loading conditions.

Results and discussion

Engine performance parameters

Figure 2 presents the plot of variation of BTE with different energy shares of the inducted eucalyptus oil, methanol, and ethanol at 100% and 40% loads while using MO as pilot fuel. The load of the engine represents the brake power output from the crank shaft at the dynamometer side. For this present study, 100% and 40% loads represent 3.7 kW and 1.48 kW power output of the engine. The BTE with MO was noted as 25.6% when used in the single fuel mode at 100% load, where as it was about 30.8% with conventional diesel. In dual fuel mode of operation using MO as pilot fuel, there was a considerable improvement in BTE with all the inducted primary fuels mainly at 100% load. It increased to a maximum of 32.3, 30.5, and 28.4%, respectively, with eucalyptus oil, ethanol, and methanol as primary fuels. The optimal energy shares for the maximum thermal efficiencies were noted as 45, 27.3, and 23.2%, respectively, with eucalyptus oil, ethanol, and methanol at 100% load. The increase in BTE could be explained by the dual combustion process occurring in the engine. It is reported that in dual fuel engines the combustion of the fuel takes place in three stages. The first phase of combustion is due to the ignition of the injected pilot fuel and the second phase of combustion is due to the combustion of the primary air-fuel mixture present in the vicinity of the combustion centres of the pilot fuel spray. The third phase is due to the flame propagation of the primary air-fuel mixture [9].

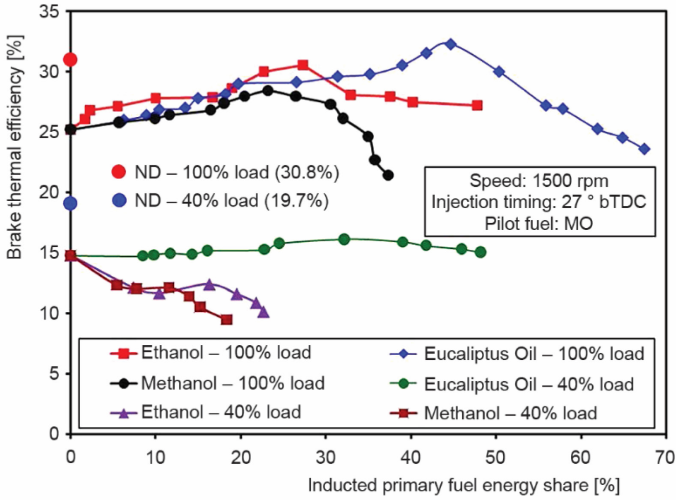

Figure 2. Variation of BTE with different primary fuels energy share

The spontaneous ignition of the injected pilot fuel combined with the flame propagation in the primary air-fuel mixture improved the heat release rates and resulted in higher BTE mainly at high power output. However, beyond the maximum efficiency points (MEP) there was a drop in BTE with all the inducted fuels. The drop in BTE could be explained by the deterioration in combustion of the inducted fuels as a result of the ignition source to be weak due to the reduced pilot fuel (MO) quantity by the governor's action. It is seen from fig. 2 that eucalyptus oil resulted in maximum thermal efficiency when contributing the energy share of 45% (which is maximum among the inducted primary fuels such as to ethanol and methanol for maximum efficiency conditions). It can be explained that the cetane number of eucalyptus oil is much higher than ethanol and methanol which resulted in reducing the ignition delay of the engine. The lower latent heat of vaporization (comparatively lower than ethanol and methanol) of eucalyptus oil helped in maintaining the charge temperature at higher levels than the other fuels. In addition the self-ignition temperature of eucalyptus oil was also lower than ethanol and methanol. All these factors have helped in extending the misfire limit of ethanol. Hence the energy share was extended for the maximum thermal efficiency with eucalyptus oil as primary fuel.

Emission parameters

The variation of smoke emission with different inducted primary fuels for 100% and 40% loads is indicated in fig. 3. In single fuel mode of operation with the NMO operation smoke emission was found to be very high at both loads. At 100% load the smoke level was observed as 78% with NMO and 51% with neat diesel. In Diesel engines smoke originates mainly from the injected fuel droplets. Due to the course droplets as a result of poor atomization of the NMO very high smoke emissions were observed at both loads. Examining the results of dual fuel operation, fig. 3 clearly shows that dual fuel operation significantly reduced the smoke emissions at all rates of primary fuel admission at both loads when MO was used as pilot fuel. The smoke emission was reduced to a minimum value of 41, 48, and 53%, respectively, with eucalyptus oil, ethanol, and methanol at the optimal energy shares (*i. e.* energy share at MEP). The reduction in smoke emission in dual fuel operation can be explained by a number of factors. Firstly the rapid flame propagation due to burning of the primary air-fuel mixture promoted the premixed combustion phase of the fuels.

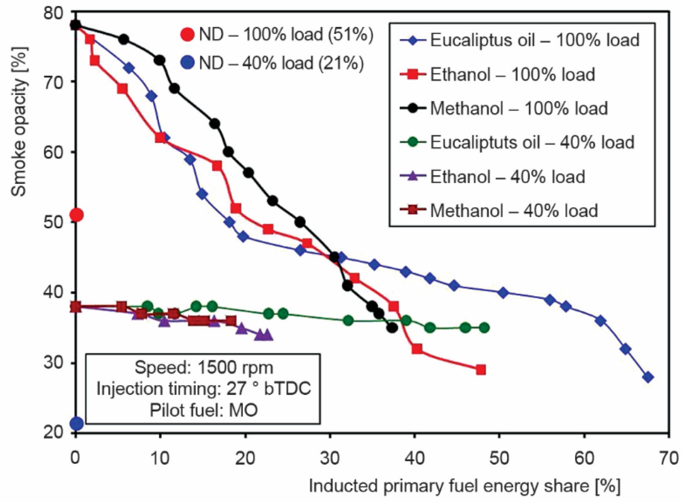

Figure 3. Variation of smoke opacity with different primary fuels energy share

The longer ignition delay of the dual fuel engine resulted in more fuel to be combusted in the premixed phase itself and hence the premixed combustion phase became significant in dual fuel operation. Secondly the increased hydrogen to carbon ratio of the primary fuels may have the tendency to reduce the smoke emission. Thirdly the reduced pilot quantity of MO injected reduced the fuel rich pockets present in the combustion chamber and reduced the smoke formation. All these factors have helped in reducing the smoke emission in dual fuel mode of operation with all the primary fuels. It must be noted that the smoke values in dual fuel mode of operation were still lower than ND operation with all the primary fuels. As for as the primary fuels are concerned, eucalyptus oil showed more reduction (47% reduction) in smoke emission as compared to other fuels (38% and 32% reduction in smoke, respectively, with ethanol and methanol) at 100% load at MEP. This can be explained by more replacement of pilot fuel by the eucalyptus oil at MEP. At 40% load due the reduced pilot quantity (as stated earlier) of the injected MO the smoke emission was reduced at all rates of the primary fuel energy shares.

The variation of NO emission with MO as pilot fuel in dual fuel operation with different primary inducted fuels is depicted in fig. 4. The NO formation in Diesel engine is due to the availability of oxygen and higher cycle temperature. The atomic nitrogen combined with the local oxygen molecules present in the combustion chamber form NO_x. The NMO resulted in lower NO emissions as compared to ND operation due to inferior combustion of the high viscous MO. It is interesting to see that in dual fuel operation with all the inducted fuels there is a considerable reduction in NO emission at both power outputs at all energy shares. In NO emission dual fuel operation is mainly associated with the reduction in the intake charge temperature NO reduced from 312 ppm (with NMO) to a minimum of 234, 162, and 143 ppm, respectively, with eucalyptus oil, ethanol, and methanol at 100% load at their MEP.

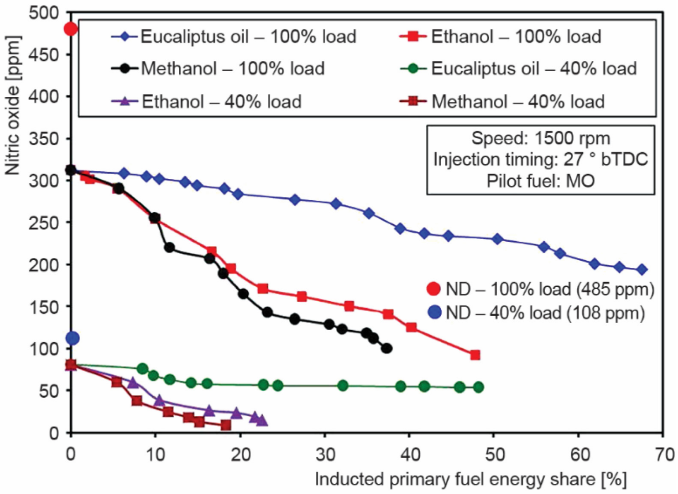

Figure 4. Variation of NO with different primary fuels energy share

The reductions due to vaporization of the inducted primary fuels were noted as 54, 48, and 25%, respectively, with methanol, ethanol, and eucalyptus oil as compared to NMO operation at 100% load. It can be noted that among the inducted fuels methanol induction showed lowest NO value of all. It is clearly understood that the very high latent heat of vaporization of methanol caused more reduction in the charge temperature as compared to other two fuels. Similar reduction in NO emission was also noted at 40% load with all the inducted fuels. Eucalyptus oil showed less reduction than the other fuels even at higher energy shares due to the latent heat of vaporization to be sufficiently higher as compared to ethanol and methanol.

The CO also exhibited an increasing trend for all the inducted fuels using MO as pilot fuel in dual fuel operation as seen in fig. 5. It is seen that at high rates of inducted fuels the raise became very high. The increase in CO emission with increase in primary fuel energy share could be attributed to the flame quenching due to the cooling effect of the charge which affected the complete oxidation of the carbon atoms in the fuel. It has been reported that the low temperature of the in cylinder charge leads to inadequate support for the combustion and results in increased CO emissions [14]. At MEP of 100% load the CO emission was found as 0.45, 0.3, and 0.35%, respectively, with eucalyptus oil, ethanol, and methanol where as it was 0.26% with NMO and

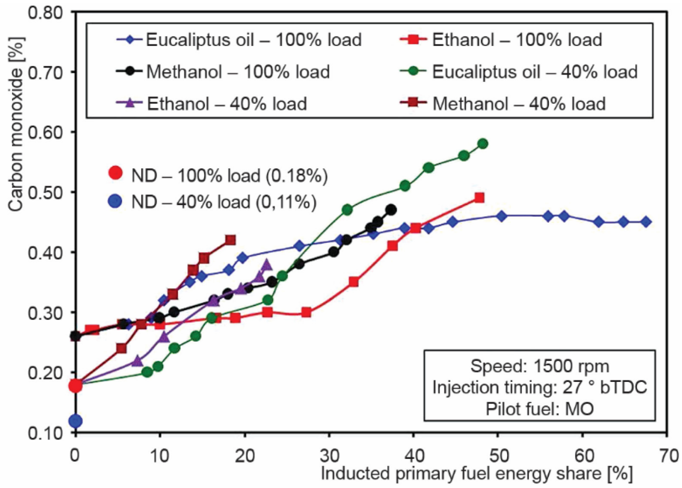

Figure 5. Variation of CO with different primary fuels energy share

0.18% with neat diesel. It is observed that the raise in CO emission becomes very significant at 40% load and at high rates of primary fuel admission. At high rates as the ignition source became too weak to ignite the primary air mixture the CO emission increased to very high levels at both loads mainly at higher energy shares. Similar trends were observed in the past studies and reported that the low cetane number of the primary fuels has rendered the fraction of the fuels trapped in crevices regions and expelled it during the expansion stroke at low loads [21]. This is also responsible for the higher HC emissions which will be explained later.

Figure 6 presents the variation of HC emission with different inducted fuels at different energy shares for 100% and 40% loads. In dual fuel operation with all the inducted fuels there is a significant rise in HC emission at both power outputs. It increased from 176 ppm (with NMO) to a maximum of 260 ppm, 323 ppm, and 402 ppm, respectively, with eucalyptus oil, ethanol, and methanol at the maximum efficiency conditions at 100% load. Generally the HC formation in dual fuel engine follows similar mechanism as to that of a spark ignition engine. Firstly as the latent heat of vaporization of the inducted fuels was very high the intake charge temperature was reduced considerably. Hence the flame propagation was affected at higher rates of primary fuels. It caused flame to be quenched and hence the unburned primary fuel was present in the quench layer. The presence of unburn primary fuel in the quench layer did not participate in the main combustion process and exhausted as unburned fuel. Secondly the charge trapped in the crevice volumes of the combustion chamber may have also contributed to significant raise in HC emissions in dual fuel mode of operation. As compared to ethanol and methanol eucalyptus oil resulted in lower HC emissions even though the energy share is very high. This trend can be explained by the comparatively lower latent heat of vaporization as mentioned already of the eucalyptus oil as compared to ethanol and methanol. At 40% load the raise in HC emission was found to be very significant for all the inducted fuels. At low load due to the large amount of air (lean mixture), poor utilization of the primary fuel, low intake charge temperature and reduced pilot fuel quantity the combustion process was completely affected. Flame quenching may have caused due to the lean mixture conditions at low load. Hence the yield of HC emission in the exhaust became very high.

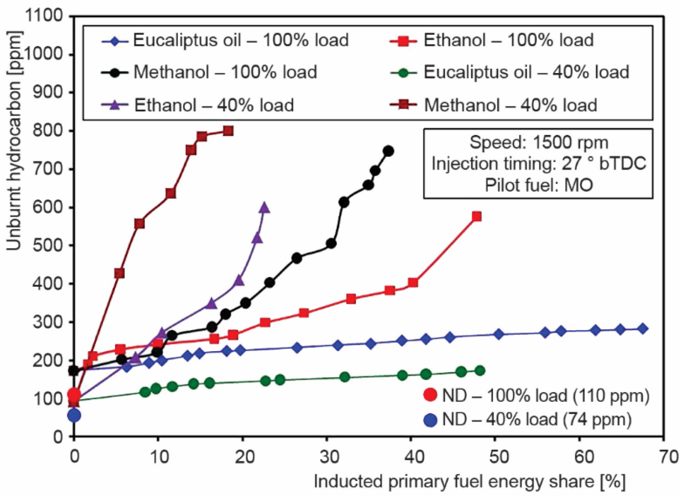

Figure 6. Variation of unburnt HC with different primary fuels energy share

Engine combustion parameters

The average cylinder pressure data obtained from 100 consecutive cycles with CA degrees and heat release rate pattern for dual fuel operation at 100% (3.7 kW) load is presented in fig. 7. In a compression ignition engine, the peak pressure depends on the combustion rate in the initial stages, and occurs close to TDC generally. In single fuel mode the maximum

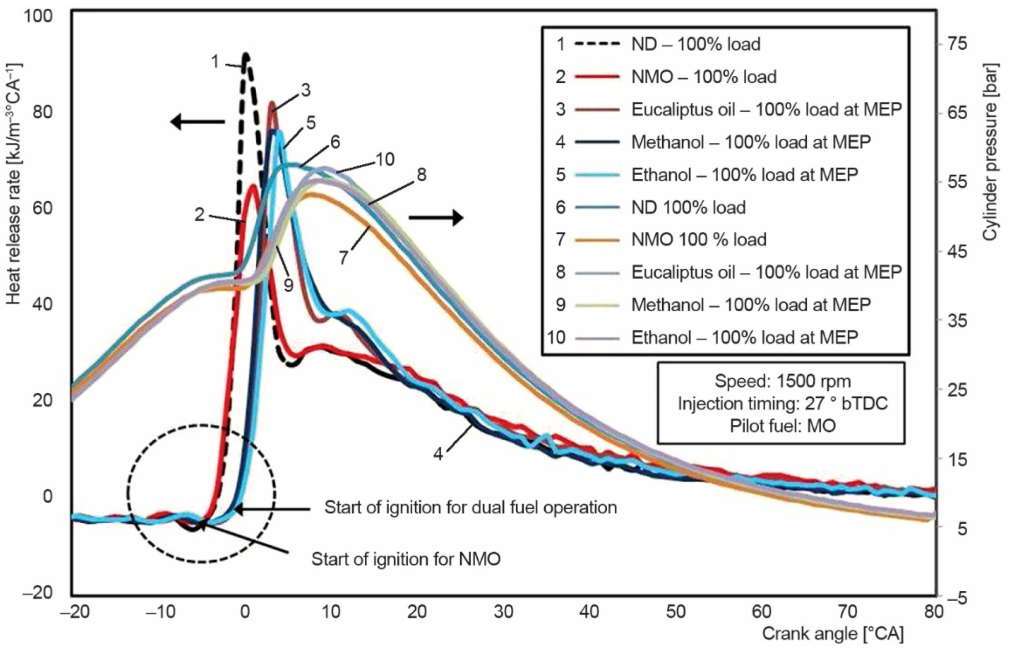

Figure 7. Variation of cylinder pressure, CA and heat release rate at 100% load

pressure was found as 57.5 bar with ND and 51.4 bar with NMO at 100% load. The cylinder pressures were similar to that of ND and NMO when the engine was operated in dual fuel mode. The maximum pressure was noted to be 57.2, 55.2, and 55 bar, respectively, with eucalyptus oil, ethanol, and methanol for 100% load. It was also noted that the occurrence of peak pressure has shifted away from TDC position (from 2-4 °CA) with all the inducted fuels at the optimal energy shares (even with the optimised injection timing of 27° bTDC). This shift in occurrence of peak pressure can be well explained mainly by the increase in ignition delay with all the inducted fuels. It can be seen from fig. 7 that the peak pressure was highest with eucalyptus oil followed by ethanol and methanol. As the energy release with eucalyptus oil was more as compared to ethanol and methanol at MEP the peak pressure was more with eucalyptus oil. At 40% load all the inducted fuels indicated reduced peak pressure.

The heat release rate pattern of a Diesel engine is the main parameter to characterise the combustion process in Diesel engines. It measures the chemical conversion and rate of conversion of fuel energy to heat. The heat release calculation was done by considering the first law of conservation of energy principle using the averaged pressure CA histories. 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. With MO as sole fuel in single fuel operation the heat release rate reduced significantly in the early stage of combustion as compared to neat diesel. The mixing controlled combustion was noted to be predominant as seen in fig. 7. This effect was due to slow burning nature of the NMO as compared to diesel. In the dual fuel operation there is a significant improvement in heat release rate particularly in the premixed combustion phase with MO as pilot fuel mainly at 100% load for all the inducted fuels. The delay in start of ignition can be easily seen with all the fuels in the heat release rate pattern. The premixed combustion phase became significant with all the inducted fuels and the diffusion phase was found to be less significant. It indicated that the heat release rate was very rapid in dual fuel mode of operation even though there is a delay in start of ignition. This is the main reason for the improved BTE in dual fuel mode of operation with all the inducted fuels. Considerable portion of the heat release rate is due to the flame propagation of the primary fuels. The delay in start of ignition can be explained by the prolonged ignition delay of the dual fuel engine. The reduction in diffusion combustion phase can be responsible for the significant reduction in smoke emissions with all the fuels in dual fuel operation. It is further noticed that the occurrence of peak heat release rate was delayed for all the inducted fuels by 2-4 °CA in comparison with neat fuel operation. However, the end of combustion was noted to earlier which indicated the fast combustion rate of the fuels in dual fuel mode of operation. Looking at fig. 7 it is seen that eucalyptus oil resulted in higher peak in heat release rate as compared to that of ethanol and methanol. It can be explained that for the maximum efficiency condition eucalyptus oil contributed more energy as compared to ethanol and methanol. Referring to the cylinder pressure CA histories eucalyptus oil resulted in peak the eucalyptus oil more heat release rate. For all the tested fuels the peak heat release was delayed. For methanol it was more as compared to ethanol. This can be explained by the very high latent heat of vaporisation of the fuel.

The variation of peak cycle temperature with different inducted fuels in dual fuel mode of operation can be seen in fig. 8 for 100% and 40% loads.

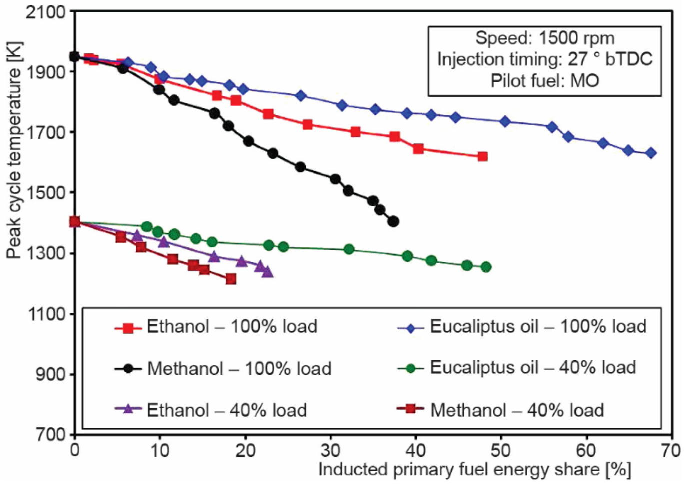

Figure 8. Variation of peak cycle temperature with different primary fuels energy share

The cycle temperature was calculated from the ideal gas law of thermodynamics using the pressure CA variations. The charge temperature at the intake valve closure was assumed to be 303 K. The mass of the fuel admitted was calculated from the fuel consumption. The maximum cycle temperature was found as lower with NMO as compared to ND in the normal engine operation at both loads. It was noted as 1950 K and 2235 K, respectively, with NMO and ND at 100% load. It is seen that there is a reduction in cycle temperature in dual fuel operation with all the inducted fuels. It reduced to a minimum of 1807, 1725, and 1630 K, respectively, with eucalyptus oil, ethanol, and methanol at their optimal energy shares at 100% load. The reduction in cycle temperature in dual fuel operation can be explained very well by the high latent heat of vaporization of the inducted primary fuels. The reduction bulk temperature is mainly responsible for the lower NO emission with all the primary inducted fuels in dual fuel mode. It is also responsible for the increased CO emissions in dual fuel mode of operation. Methanol indicted more reduction in cycle temperature due to its very high latent heat of vaporization.

Conclusions

In the dual fuel operation with eucalyptus oil, ethanol, and methanol as inducted fuels, there is an appreciable improvement in engine's performance as compared to NMO operation, mainly at 100% load and moderate admissions of all the inducted fuels. The maximum BTE was arrived as 32.3, 30.5, and 28.4%, respectively, with eucalyptus oil, ethanol, and methanol as primary fuels whereas it was 25.6% with NMO and 308 with ND. Considerable reduction in smoke and NO emissions were achieved in dual fuel operation with all the inducted fuels at 100% and 40% loads. Significant improvement in the initial stage of the heat release rate was noted at 100% load with all the inducted fuels. The optimal energy share for the best combustion behaviour was found to be 44.6, 27.3, and 23.2%, respectively, for eucalyptus oil, ethanol, and methanol at 100% load. Eucalyptus oil showed the best on engines performance, emission, and combustion behaviour among the inducted fuels. In general, dual fuel operation showed inferior combustion behaviour at 40% load for all the inducted fuels. As for as the economic aspect is concerned, the use of MO as a replacement to conventional diesel fuel in Diesel engines under dual fuel mode of operation could considerably reduce the foreign oil imports of a country if adopted in with approbiate modification in engine side. Dual fuel operation with renewable fuels such as eucalyptus oil, ethanol and methanol as inducted fuels with MO as main fuel could achieve pollution free exhaust from diesel engines. However the part load performance and increase in HC and CO emissions need attention.

Nomenclature

bTDC – before top dead centre
BTE – brake thermal efficiency, [%]
CA – crank angle, [°]
MEP – maximum efficiency point
MO – mahua oil
ND – neat diesel
NMO – neat mahua oil

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