A COMPREHENSIVE STUDY ON THE EFFECT OF EMULSIFICATION, SOLID NANOADDITIVE, AND LPG DUAL FUEL OPERATION ON ENGINE BEHAVIOUR OF A WCO BASED COMPRESSION IGNITION ENGINE

by

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The influence of emulsification, solid nanoadditive and liquefied petroleum gas (LPG) dual fuel operation on engine's performance, emission and combustion behaviour of a waste cooking oil (WCO) of sunflower oil based compression ignition engine was studied experimentally. Initially test engine was operated in single fuel mode with neat diesel, and neat waste cooking oil (NWCO) as fuels at various loading conditions. In the second phase WCO was converted into its emulsion (WCO-EM) and tested in the engine. The WCO-EM was further modified into solid nanoadditive emulsion (WCO-NF-EM) and tested. Finally the engine was modified to operate in dual fuel mode, and tested with LPG as the inducted fuel with WCO-NF-EM as pilot fuel. The NWCO resulted in inferior engine operation with higher smoke, HC, and CO emissions as compared to neat diesel all power outputs. Significant improvement in brake thermal efficiency was noted with all the methods attempted. Dual fuel operation with WCO-NF-EM-LPG showed highest brake thermal efficiency which is very close to diesel value. Smoke and NO_x *emissions were considerably reduced with all the methods. Dual fuel mode with LPG induction showed the lowest smoke emission which was still lower than diesel value. The WCO-EM and WCO-NF-EM further reduced the HC and CO emissions at all power outputs. It is concluded that the WCO can be effectively used in Diesel engines by converting into its solid nanoadditive emulsion in the unmodified engine. Combining dual fuel operation with WCO-NF-EM-LPG could achieve the engine operation similar to diesel.*

Key words: *Diesel engine, nanoadditive, emulsion, liquefied petroleum gas, dual fuel engine, engine performance, emission, combustion*

Introduction

Vegetable oils show most promising alternative fuel for Diesel engine due to their favourable properties very close to diesel fuel [1, 2]. Earlier studies have reported significant engine results with different vegetable oils as fuels [3-5]. However, the use of edible oils directly affects the consumer in cost and availability when used as engine fuel. In this regard used cooking oil looks very attractive to use as fuel for Diesel engines. Past engine studies revealed that waste cooking oil (WCO) could be used in Diesel engines as fuel [6, 7]. However, international standards prevent the straight usage of such oils in a unmodified Diesel engines. The WCO could be used as fuel in diesel engines effectively with little modifications either in fuel or in engine side. Transesterification is one of the widely used fuel modifications for converting neat WCO into

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its ester [8, 9]. This process has the advantages of reduced viscosity, improved cetane number as compared to its neat oil. But complexity and cost factor makes the transesterfication process as an unfavourable method. Emulsification process shows another option in using WCO effectively as fuel in Diesel engines [10, 11]. Earlier research studies reported simultaneous reduction of oxides of nitrogen and smoke emissions in Diesel engines emulsified vegetable oils as fuel [10, 11]. Hence modifying the WCO into its stable emulsion and using as fuel can achieve superior thermal efficiency and reduced smoke and NO_x emissions. Recent studies indicated involvement in nanotechnology in improving the engines performance using nanofluids as fuels and promising result outcomes were reported in recent times [12-14]. Nanofluids are the fluids dispersed with nanoparticle in the homogeneous liquids. Nanofluids find a wide range of applications in engine propulsion system, engine cooling system *etc*. due to its high thermal conductivity. Nanofluids are also used as fuel additives to enhance combustion behaviour of HC fuels in engines. Researchers reported that the oxidation of metal content of nanofluid tends to produce more heat as compared to diesel and other fuel when used as an additive along with them. Experiments conducted with four different nanocatalysts such as cerium, iridium, palladium, and rhodium in a compression ignition engine resulted in improved combustion and emission characteristics of biodiesel blend [12].

Dual fuel operation in Diesel engines is considered as another important option to use vegetable oils effectively under engine modification side. Fuels possessing high octane number such as alcohol, hydrogen, liquefied petroleum gas (LPG) are generally preferred as primary fuels and the fuels having high cetane number like diesel, vegetable oil are used as pilot fuel [15-17]. Past investigations reported significant improvement in engines performance and reduced smoke and NO_x emissions with alcohol as primary fuel using vegetable oil as pilot fuel [15]. However, alcohols result in higher HC and CO emissions at all operating conditions of dual fuel operation. Though hydrogen is very attractive fuel for primary fuel operation, the very high flame seed and low ignition energy of hydrogen cause pre ignition and backfire problems if used as fuel. The LPG looks very promising fuel for engine operation due to its availability, safety and storage. Earlier investigations on LPG as primary fuel in dual fuel reported promising results with diesel and vegetable oil as pilot fuels [18-20].

It is clear from the previous studies that emulsifying the oil is a simple and effective method of using vegetable oils in Diesel engines as fuel. However, past research indicated no results on the influence of nanoadditives with vegetable oil emulsions as fuel on engines behaviour of Diesel engines. In addition the combined effect of LPG dual fuel operation with WCO solid nanoadditive emulsion (WCO-NF-EM) as pilot fuel on engines performance, emission and combustion behaviour of Diesel engines was not reported so far. Adding solid nano- additives with the emulsions and using them as fuel could achieve significant improvement in engines performance and reduction in all the emissions. Best engine operation can be achieved by adopting dual fuel operation with LPG as inducted primary fuel and WCO emulsions with nanoadditive as injected pilot fuel. An attempt was made to use WCO effectively in a Diesel engine. In the first-phase the engine was tested for its performance using neat WCO as fuel followed by WCO-EM. In the second-phase solid nanopowder (Al_2O_3) was mixed with WCO-EM by using an ultrasonic agitator and tested as fuel under variable load conditions. Finally the intake system of the engine was modified to accommodate LPG for dual fuel operation and engine tests were conducted using WCO-NF-EM as pilot fuel with LPG as primary fuel at different power output with varying amount of LPG to optimise the energy share. All the methods were compared at 20%, 40%, 60%, 80%, and 100% power outputs.

Fuel preparation and properties study

For the engine trials WCO of sunflower was procured form the institute hostel for about 25 litres. Collected WCO was filtered with course and fine filters and properties such as viscosity, density lower heating value were measure. The measured properties can be seen in tab.1.

Table 1. Properties of fuels

Properties	ND	NWCO	WCO-EM	WCO- NF-EM	ASTM standard
Viscosity, [cst]	4.6	45	49	44	D 445
Density, [Kgm^{-3}]	840	886	895	880	D 1298
Low heating value, [kJkg^{-1}]	43500	40000	38000	41000	D 5865
Cetane number	45	37	42	44	D 613

(ND – neat diesel, NWCO – neat waste cooking oil, WCO-EM – waste cooking oil emulsion
WCO–NF–EM – waste cooking oil solid nanoadditive emulsion)

The WCO-EM preparation

Emulsions are generally obtained by mixing two immiscible liquids in the presence of a stabilizer called as surfactant. The surfactant permits the water to get mixed well with oil. It reduces the interfacial tension of the oil and allows the water droplets to get dispersed uniformly in the continuous oil phase. The choice of surfactant is important because it influences the type of emulsion formation and its stability. For the present work, surfactant having HLB value less than 7 has to be used for preparing water in oil emulsion. Hence SPAN 80 (with HLB value as 4.2) was chosen as the best surfactant for making water WCO-EM. The WCO-EM were prepared by using a mechanical agitator which rotated at the speed of 2000 rpm. Initially a number of trials were made with different combinations of water, oil, surfactant and co surfactant. Ternary diagram shown in fig. 1 was plotted to study the stability of the prepared emulsions. From the stability point the mixture of 75% of WCO, 15% of water, 5% of SPAN 80, and 5% ethanol by volume resulted in maximum stability for 10 days. Hence the previous combination was selected for engine tests. The same was used for preparing the WCO-EM with solid nanoadditive as well.

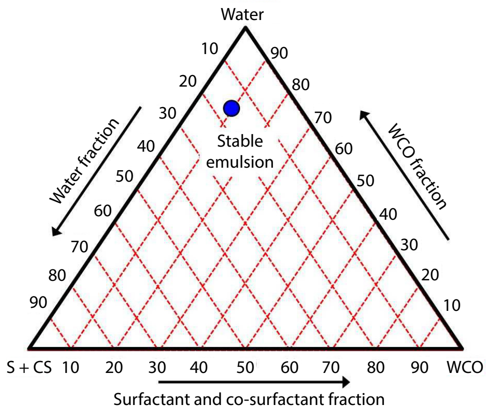

Figure 1. Ternary diagram for stable emulsion

Figure 2. Ultrasonic agitator and mechanical stirrer arrangement

Solid nanopowder addition

Nanofluids are the fluids with dispersed nanoparticles present in it. The WCO-NF-EM was prepared by using an ultrasonic agitator and the mechanical stirrer as shown in fig. 2. For the work is Al_2O_3 of size 50-60 nm was selected for preparing the WCO solid nanoaddditive emulsion due to its better thermal conductivity. Initially 50 ppm of Al_2O_3 nanoparticles was made dispersed in 15% by volume of water with help of the ultrasonicator. The ultrasonic agitator was allowed to operate at the amplitude of 20 μm with a frequency of 20 kHz for a period of 30 minutes for the complete dispersion of nanoparticles in the water. Prepared nanopowder was mixed well with WCO-EM with the help of mechanical agitator to obtain the WCO-NF-EM. From the stability test it was observed that the nanoadditive with the WCO-EM was stable for 7 days.

Engine experimental set-up and experiments conducted

The engine used for this work was a constant speed, single cylinder, water cooled, naturally aspirated, compression ignition engine with the rated power output of 3.7 kW at 1500 rpm. Burette and stop watch arrangement was used to measure the fuel-flow rate. Engine speed was measured by an inductive pick and the torque was measured by an eddy current dynamometer (BENZ SYSTEMS) coupled directly with the engine. 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 as percent by volume as standard units. Black carbon smoke levels were obtained by using a standard AVL smoke meter. The in cylinder pressure crank angle (CA) histories were obtained by using a KISTLER air cooled piezo electric pressure sensor and a AVL TDC encoder fitted at the crank shaft. An AVL INDISMART combustion analyser was used for acquiring the pressure CA histories. The details of the instruments used for the experiments and their uncertainty can be seen in tab. 2. The test engine set-up can be seen in fig. 3.

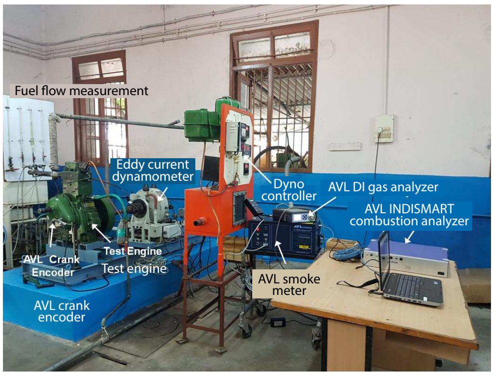

Figure 3. Photographic view of the test engine set-up

Table 2. Details of used instruments and their uncertainty details

Parameter	Instrument used	Measuring range	Accuracy	Percentage uncertainty
Brake power, [kW]	Eddy current dynamometer (Benz systems)	0-50 kW	± 0.5 kW	±1% kW
Fuel-flow rate, [gs^{-1}]	Burette and stop watch	0-200 g	0.5 g	±2% gs^{-1}
In-cylinder pressure	AVL Indi smart with Kistler pressure sensor	0-100 bar	±0.1 bar	±1.2% bar
Carbon monoxide, [%]	AVL Digas 444 five gas analyzer	0-10% (vol)	±0.03%	±0.8%
Hydrocarbon, [ppm]	AVL Digas 444 five gas analyzer	0-20000 ppm (vol)	±10 ppm	±0.9% ppm
Oxides of Nitrogen, [ppm]	AVL Digas 444 five gas analyzer	0-5000 ppm (vol)	±10 ppm	±1% ppm
Smoke opacity, [%]	AVL 437 C smoke meter	0-100%	± %	±1%

The engine was initially run with neat diesel (ND) and NWCO as fuels in single fuel mode at different loading conditions such as 20%, 40%, 60%, 80%, and 100% loads (power outputs) to provide baseline reference. Engine experiments were repeated with WCO-EM and the WCO-NF-EM as fuels for comparison. Finally dual fuel operation was achieved by inducting the primary fuels along with air during the suction stroke of the engine by using a LPG induction system. The amount of primary fuel (LPG) admission was varied by using a flow control unit and the amount of gas supplied was measured by a gas-flow meter. 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 °CA intervals for each method. The engine's brake thermal efficiency (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 WCO, WCO-EM, and WCO-NF-EM. The same injection timing was used for dual fuel operation also. The optimal injection timing for diesel was 23 °bTDC. The LPG admission was varied from 0 to the maximum possible limit until the engine knocks or misfire and found as 22% for the best efficiency at 100% load. The variable load tests were carried out with the fixed LPG share of 22% for dual fuel operation with WCO-NF-EM as pilot fuel. 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. Combustion pressure CA histories were acquired by the AVL combustion analysers. All the experiments were repeated three times to check for repeatability in measured values.

Results and discussion

Engine performance characteristics:

Variation of BTE with brake power of ND, NWCO, WCO-EM, and WCO-NF-EM, and the WCO-NF-EM-LPG could be seen in fig. 4.

It is clear from the graph, BTE of all the fuel increased with brake power. It can be seen that NWCO resulted in lower BTE as compared to ND operation at all power outputs. It was 24% with NWCO and 31.9% with ND at the maximum power output of 3.7 kW. The reduction in BTE of NWCO is due to the incomplete combustion of the highly viscous NWCO as a result of poor atomization and vaporization process. However, with WCO-EM the BTE was observed to be superior at all power outputs and found as 26% at the maximum power output. The increase in BTE of WCO-EM is mainly due to the presence of water molecule in the emulsion which resulted in the micro-explosion of the emulsified fuel. Micro-explosion resulted in the secondary atomization of the injected fuel which could help in improvement in mixture preparation and paid for more amount of energy release due to complete combustion. Further increase in the BTE was observed with WCO-NF-EM at all power outputs as compared to WCO-EM and NWCO. It could be explained that the presence of metal based catalyst (Al_2O_3) in the WCO-NF-EM increased the mixing characteristics of injected fuel and air due to its higher surface to volume ratio. The improvement in calorific value of the WCO-NF-EM may have helped in more energy release and increased the

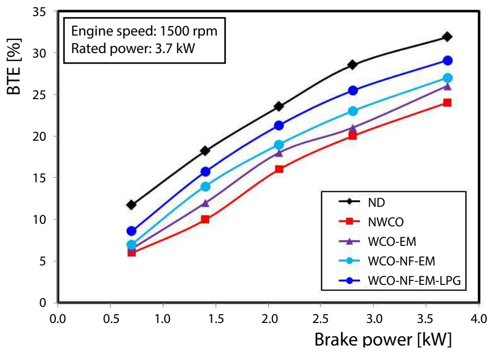

Figure 4. Variation of BTE with brake power

BTE. The BTE was noted as 27.2% with the WCO-NF-EM at peak power output. It is interesting to see that dual fuel operation with LPG induction showed further improvement in thermal efficiency of the WCO-NF-EM at all power outputs. The BTE reached to a maximum of 29.1% (which is very close to diesel value) at the maximum power output for the LPG energy share of 30%. The increase in BTE in dual fuel operation could be explained by the dual combustion process occurring in the engine. The spontaneous ignition of the injected WCO-NF-EM combined with the flame propagation through the LPG air mixture improved the heat release rates (HRR) and resulted in higher BTE.

Engine emission characteristics

The variation of HC and CO emissions with brake power for ND, NWCO, WCO-EM, WCO-NF-EM, and WCO-NF-EM-LPG can be seen in figs. 5 and 6, respectively. The HC emission was found to increase with increase in brake power for all the methods. This is due to the amount of fuel supplied to be more with raise in engine power. Due to the fixed air supply in Diesel engines, the air/fuel ratio becomes rich when the load is increased. Hence the oxygen availability is reduced at higher power outputs and results in higher HC emissions. The NWCO resulted in higher HC emissions as compared to ND at all power outputs. The maximum value of HC was found to be 150 ppm at peak power output where as it was 80 ppm with ND. The high viscosity and slow burning nature of vegetable oil based fuels may be the reason for the increased HC emission with WCO. The WCO-EM showed lower values of HC emissions at all power outputs as compared to NWCO. It can be explained by micro-explosion of the emulsified fuel which improved the atomization characteristics of WCO-EM, resulted in better mixing of fuel and air and improved the rate of combustion. Use of WCO-NF-EM reduced the HC emissions further at all power outputs as seen in fig. 5. The reduction in HC emission with the solid nanoadditive emulsion may be explained by the presence of oxygen in the nanopowder which helped in oxidation of the HC fuel as reported by Vijayakumar *et al*. [20]. It has been reported by Mirzajanzadeh *et al*. [13] that the higher surface to volume ratio of Al_2O_3 may result in better mixing of air and injected fuel which helps in increased rate of combustion. All these factors may have involved in complete combustion of WCO-NF-EM.

The CO indicated in fig. 6 increased with increase in engine's power with all the methods as expected due to the reduced availability of oxygen for the oxidation of partially burned CO molecules. The NWCO indicated very high levels of CO emissions as compared to ND operation at all operating conditions. The value was found to be 0.42% at peak power

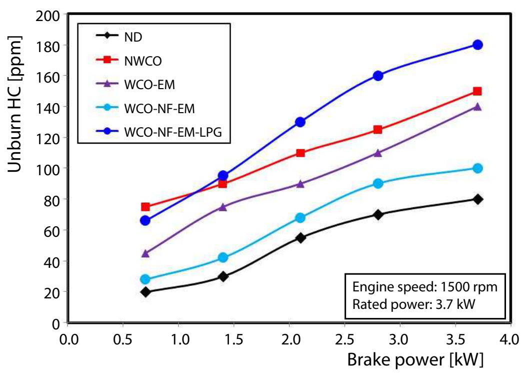

Figure 5. Variation of unburn HC with brake power

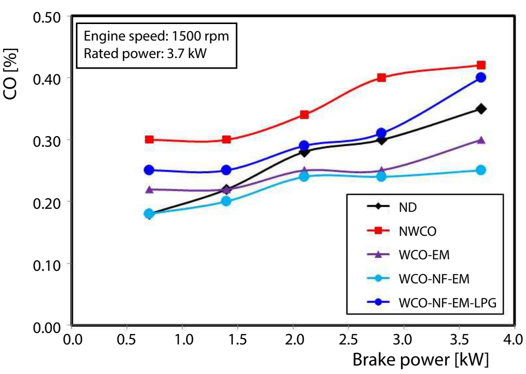

Figure 6. Variation of CO with brake power

output where as it was 0.35% with ND operation. The raise in CO emission with NWCO can be explained by the low combustion temperature of the fuel which was not sufficient to oxidise the CO formed due to inferior combustion. The WCO-EM showed reduced CO emissions as compared to NWCO at all power outputs. The reduction in CO emission with the emulsified WCO can be explained by the micro-explosion process which helped in complete combustion of the fuel even with the reduced peak cycle temperature. The value at peak power output was noted to be 0.3% with WCO-EM. Further reduction in CO emission was noted with the WCO-NF-EM at all power outputs. The CO was reduced further to 0.25% with the solid nanoadditive emulsion at peak power which is still lower than diesel value. The reduction in CO emission was noted to be 29% and 40% as compared to ND and NWCO, respectively. The reduction in WCO-NF-EM could be explained by the presence of excess oxygen content of the nanoadditive in the fuel which supported in the oxidation of CO molecule to CO_2. Thus the level of CO emission was lower. However dual fuel operation with LPG induction reported higher CO emissions at all power outputs with WCO-NF-EM as pilot fuel. In dual fuel operation with LPG admission as a result of fuel richness due to the insufficient oxygen the CO emission was noted to be higher.

The variation of NO_x and smoke emissions with brake power can be seen in figs. 7 and 8, respectively, for all the methods tried. As expected ND experienced highest NO_x emission of all the fuels used at all power outputs. On the other hand, lesser oxides of nitrogen emission were observed with NWCO as compared to ND. The values were noted to be 300 ppm with NWCO and 350 ppm with ND at peak power output. As a result of reduced cycle temperature due to incomplete combustion of the NWCO the NO_x emission was found to be lower. Conversion of WCO into its emulsion and used as fuel indicated considerable reduction in NO_x emissions at all power outputs as compared to NWCO. The higher latent heat of vaporization of ethanol and water present in the emulsion absorbed more heat for their evaporation and resulted in lesser cycle temperature. Thus WCO-EM produced 250 ppm of NO_x emission which was comparatively lesser than ND and WCO. It must be noted that the NO_x emission was further reduced with the WCO-NF-EM mainly at higher power outputs. However past studies reported increase in NO_x with the solid nanoadditive emulsion as fuel. The reduction in NO_x emission with the WCO solid nanoadditive emulsion could be due to the availability of less oxygen participated in formation of NO_x. Referring to the fig. 7 that CO emission was minimal for the WCO-NF-EM at all power outputs which indicated that the availability of oxygen was utilised mainly for the formation of CO_2 was more. The NO_x emission was recorded as 180 ppm with the WCO solid nanoadditive emulsion at the maximum power output. However, dual fuel operation indicated raise in NO_x at all power

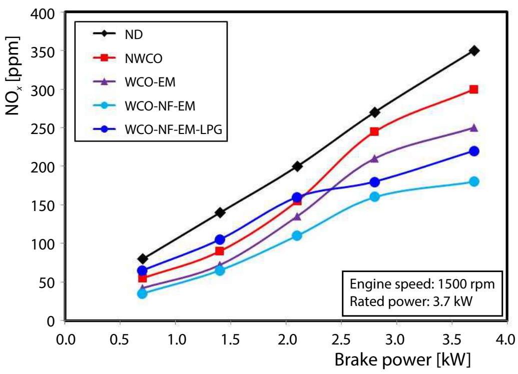

Figure 7. Variation of NO_x with brake power

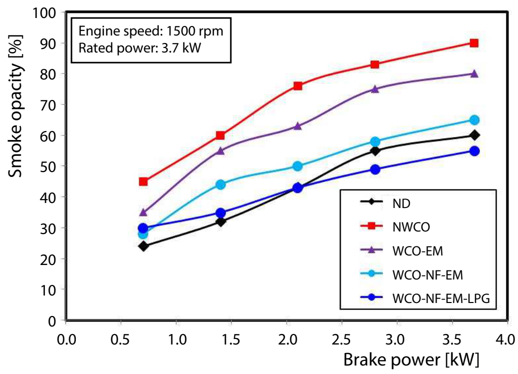

Figure 8. Variation of smoke opacity with brake power

outputs due to the fast burning nature of the LPG which increased the cycle temperature of the engine.

Experimental results presented in fig. 8 indicated very high levels of smoke emissions with NWCO at all power outputs as compared to ND. The value was noted to be 90% and 60%, respectively, for NWCO and ND at peak power output. The very high viscosity which is about 10 times higher than ND leads to poor atomisation of the injected fuel which resulted in course droplets to be present in the combustion chamber. Poor mixture preparation due to its higher viscosity and lower volatility reported maximum smoke values with NWCO at all power outputs as compared to ND operation. However, the emulsified WCO (*i. e.* WCO-EM) reported comparatively lesser smoke emissions (80%) as compared to NWCO. It is mainly due to the secondary atomization of injected emulsified fuel because of the phenomenon called as micro-explosion. Inclusion of Al_2O_3 solid nanoadditive with the WCO-EM further reduced the smoke emission of the engine operated on WCO-NF-EM to a minimum of 65%. The previous statement can be supported by the higher surface to volume ratio of the nanoparticles which helped in the better mixture formation and resulted in the reduction of smoke emissions at all power outputs. Dual fuel operation with LPG induction further reduced the smoke values of WCO-NF-EM mainly at high power outputs. At peak power output the smoke value was observed to be 55% which is noted to be still lower than ND value. In dual fuel operation with LPG induction the smoke reduction could be explained mainly by the combustion process of the engine following the spark ignition combustion process. Induction of LPG achieved the constant volume combustion and reduced the smoke emissions at all power outputs. Due to the induction of LPG the injected pilot fuel quantity was also reduced due to the governor's role. Hence the smoke forming droplets from the pilot fuel were minimised. The smoke reductions with different methods were noted to be 11%, 28%, and 39%, respectively, with WCO-EM, WCO-NF-EM, and WCO-NF-EM-LPG as compared to NWCO at peak power output.

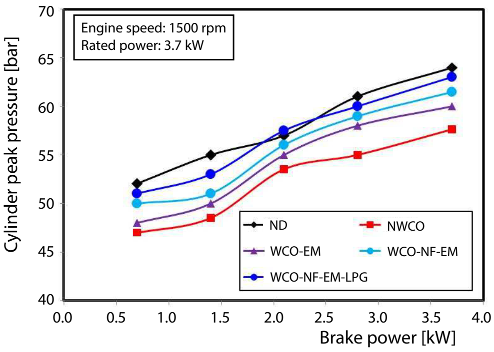

Figure 9. Variation of cylinder peak pressure with brake power

Cylinder peak pressure obtained from ensemble average of 100 cycles for ND, NWCO, WCO-EM, WCO-NF-EM, and WCO-NF-EM-LPG at different power outputs can be seen in fig. 9. The NWCO indicated lower peak pressure as compared ND at all power outputs.

The slow combustion of the NWCO due to its poor atomisation and vaporisation due to its high viscosity resulted in cylinder peak pressure to be lower than ND. The peak pressure at the rated power output was observed as 57.6 bar and 64 bar, respectively, with NWCO and ND. However, the cylinder peak pressure increased with all the methods attempted with WCO as base fuel. The peak pressure increased to a maximum of 60 bar, 61.5 bar, and 63 bar, respectively, with WCO-EM, WCO-NF-EM, and WCO-NF-EM-LPG at peak power output. The increase in peak pressure with WCO-EM can be explained by the improvement in premixed burning rate of the HRR. The low cetane number of the emulsion resulted in increased ignition delay which caused a strong premixed combustion phase and gave rise in the cylinder peak pressure. As the combustion was accelerated due to the presence of nanoparticles in the WCO-NF-EM the peak pressure increased further. In dual fuel operation the peak pressure developed depends mainly on the combustion of the primary fuel air mixture. The fast flame propagation of the LPG air mixture enhanced the combustion rate and increased the cylinder peak pressure with WCO-NF-EM as pilot fuel.

The variation of HRR with different methods attempted can be seen in fig. 10 for the maximum output of 3.7 kW. 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. All the methods followed the trend similar to ND. The combustion was more pronounced at the diffusion phase rather than premixed phase with NWCO due to high viscosity and poor volatility. However, WCO-EM resulted in improvement in HRR at the premixed combustion period. Owing to the presence of ethanol and water fraction in the WCO-EM, the ignition delay was increased which led to prepare more amount of combustible fuel within the period of ignition delay and increased the HRR. The accelerated combustion of the WCO-NF-EM increased the premixed combustion further as compared to WCO-EM. Dual fuel operation indicted the highest premixed combustion rate of all methods which is very close to diesel pattern. The raise in HRR with the dual fuel mode of operation could be explained by the combustion process moving to constant volume combustion on account of flame propagation through the LPG air mixture.

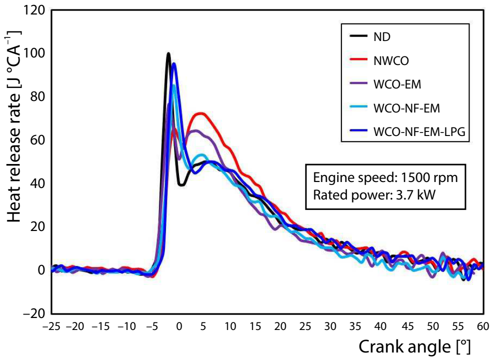

Figure 10. Variation of heat release rate with brake power (*for color image see journal web site*)

Conclusion

Effect of emulsification, solid nanopowder additive and dual fuel operation on engine's performance, emission and combustion behaviour of a WCO based Diesel engine was studied. The WCO-EM considerably increased the BTE of the engine at all power outputs with reduced smoke, NO_x, HC, and CO emissions. Conversion of WCO-EM into WCO-NF-EM and using as fuel achieved further improvement in BTE and reduction in all emissions. Dual fuel operation reached the highest thermal efficiency and lowest level of smoke values for the given engine power out. The values were very close to diesel. It was concluded that the WCO can be effectively used in Diesel engines by converting it into its solid nanoadditive emulsion in the unmodified engine. Combining dual fuel operation with WCO-NF-EM- LPG could achieve the engine operation close to diesel operation using WCO as fuel.

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