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Performance Evaluation of a High Grade Low Heat Rejection Diesel Engine with Waste Fried Vegetable Oil

R.P. Chowdary[1], M.V.S. Murali Krishna[2], T.K.K. Reddy[3], P.V.K.Murthy[4]
[1, 2]Mechanical Engineering Department, Chaitanya Bharathi Institute of Technology,
Gandipet, Hyderabad-500 075, Andhra Pradesh, India
3 Mechanical Engineering Department, College of Engineering,
J.N.T. University, Hyderabad -500 085, Andhra Pradesh, India
[4] Vivekananda Institute of Science and Information Technology,
Shadnagar, Mahabubnagar-509216, Andhra Pradesh, India

ABSTRACT

Investigations were carried out to evaluate the performance of a high grade low heat rejection (LHR) diesel engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head [ceramic coating of thickness 500 microns was done on inside portion of cylinder head] with different operating conditions [normal temperature and pre-heated temperature] of crude waste fried vegetable oil (WFVO) collected from restaurants, hotels etc., with varied injection pressure and injection timing. Performance parameters of brake thermal efficiency, exhaust gas temperature and volumetric efficiency were determined at various magnitudes of brake mean effective pressure. Pollution levels of smoke and oxides of nitrogen (NOx) were recorded at the peak load operation of the engine. Combustion characteristics at peak load operation of the engine were measured with TDC (top dead centre) encoder, pressure transducer, console and special pressure-crank angle software package. Conventional engine (CE) showed deteriorated performance, while LHR engine showed improved performance with WFVO operation at recommended injection timing and pressure and the performance of both version of the engine was improved with advanced injection timing and at higher injection pressure when compared with CE with pure diesel operation. The optimum injection timing was 32^{o}bTDC for CE while it was 31^{o}bTDC with LHR engine with vegetable oil operation. Peak brake thermal efficiency increased by 11%, smoke levels decreased by 17% and NOx levels increased by 39% with WFVO operation on LHR engine at its optimum injection timing, when compared with pure diesel operation on CE at manufacturer's recommended injection timing of 27^{o}bTDC(Before top dead centre).

Keywords: *WFVO, LHR engine, Performance, Pollution levels, Combustion characteristics.*

NOMENCLATURE

BMEP	Brake mean effective pressure in bar
BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption in kg/h-kW
bTDC	Before Top Dead Centre in degrees
BTE	Brake thermal efficiency in %
CE	Conventional engine
CL	Coolant load
DF	Diesel fuel
EGT	Exhaust gas temperature in degree centigrade
HSU	Hartridge smoke unit
LHR	Low heat rejection
MRPR	Maximum rate of pressure rise in bar/deg
NOx	Oxides of nitrogen in parts per million
NT	Normal temperature of vegetable oil in degree centigrade
ppm	Parts per million
PP	Peak pressure in bar
PT	Preheat temperature of the vegetable oil in degree centigrade
TOMRPR	Time of occurrence of maximum rate of pressure rise in degree
TOPP	Time of occurrence of peak pressure in degree
WFVO	Waste fried vegetable oil
VE	Volumetric efficiency in %

1. INTRODUCTION

In the context of fast depletion of fossil fuels, increase of prices in International Market, and increase of pollution levels with fossil fuels, the search for alternate fuels had become pertinent. The most promising substitutes for diesel fuels are vegetable oils alcohols- mainly ethanol and methanol. Alcohols have low cetane number and hence engine modification was necessary if they are to be used as fuels in diesel engines. On the other hand, vegetable oils have high cetane number, compatible to diesel fuel. Rudolph diesel, the inventor of the engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. Experiments were conducted [1-7] with CE with vegetable oils and blends of vegetable oil and diesel and reported that performance was deteriorated with CE. However the drawbacks of low volatility and high viscosity call for LHR engine. The concept of LHR engine is to prevent heat flow to the coolant by providing insulation in the path of the heat flow to the coolant. Several methods adopted for achieving LHR to the coolant were i) using ceramic coatings on piston, liner and cylinder head ii) creating air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. Ceramic coatings provided adequate insulation and improved brake specific fuel consumption (BSFC) which was reported by various researchers [8-13]. Experiments were conducted [14] on LHR engine with air gap insulated piston with superni crown, air gap insulated liner with superni insert with different fuels like non-edible vegetable oils and alcohols and reported that performance was improved with LHR engine with alternate fuels. Investigations were carried out [15] with LHR engine with air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with bio-diesel and reported that LHR engine improved performance.

Little literature was available in evaluating the performance of LHR engine with air gap insulated piston and air gap insulated liner with ceramic coated cylinder head with varying engine parameters at different operating conditions of WFVO. The present paper attempted to evaluate the performance of LHR engine, which contained an air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with different operating conditions of WFVO with varying engine parameters of change of injection pressure and timing and compared with CE at recommended injection timing and injection pressure.

2. EXPERIMENTAL PROGRAMME

The properties of vegetable oil were taken from the Reference- 14.

Fig.1gave the details of insulated piston, insulated liner and ceramic coated cylinder head employed in the experimentation. The low heat rejection diesel engine contained a two-part piston - the top crown made of low thermal conductivity material, superni-90 was screwed to aluminum body of the piston, providing a 3mm-air gap in between the crown and the body of the piston. The optimum thickness of air gap in the air gap piston was found to be 3-mm [14] for better performance of the engine with superni (an alloy of nickel) inserts with diesel as fuel. A superni-90 insert was screwed to the top portion of the liner in such a manner that an air gap of 3-mm was maintained between the insert and the liner body. Partially stabilized zirconium (PSZ) of thickness 500 microns was coated on inside portion of cylinder head.

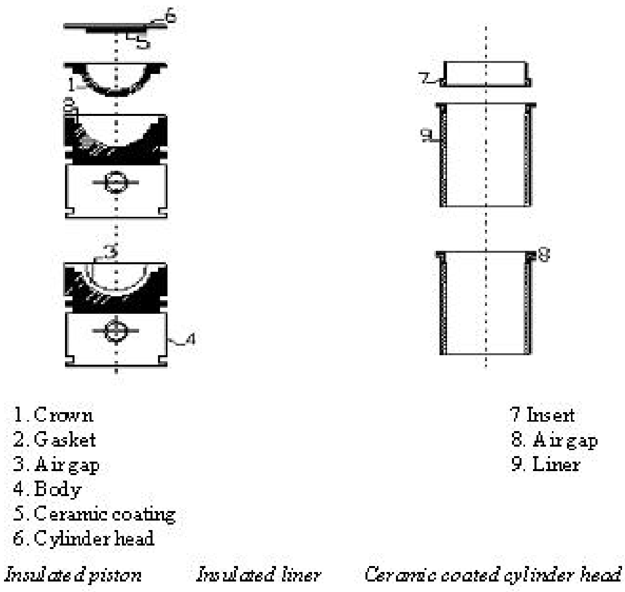
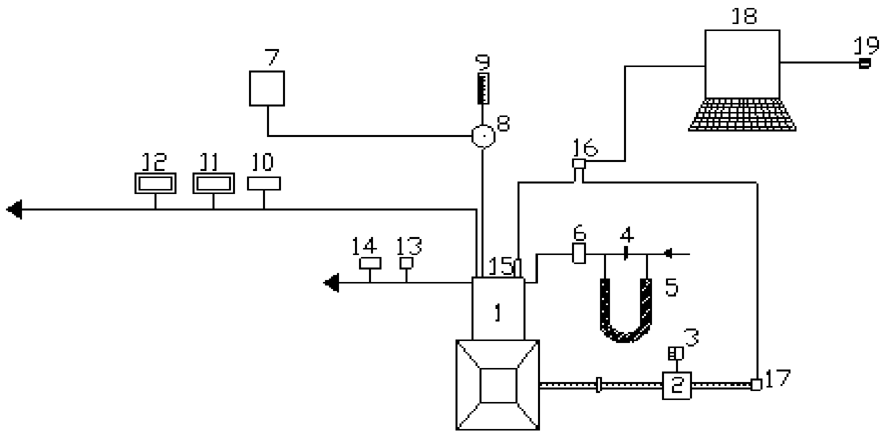


Fig.1. Assembly details of insulated piston, insulated liner and ceramic coated cylinder

Experimental setup used for the investigations of LHR diesel engine with crude waste fried vegetable oil (WFVO) was shown in Fig.2.

CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110mm. The rated output of the engine was 3.68 kW at a rate speed of 1500 rpm. The compression ratio was 16:1 and manufacturer's recommended injection timing and injection pressures were 27°bTDC and 190 bar respectively. The fuel injector had 3-holes of size 0.25-mm. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to electric dynamometer for measuring brake power of the engine. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by air-box method. The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 60°C by adjusting the water flow rate. Engine oil was provided with a pressure feed system. No temperature control was incorporated, for measuring the lube oil temperature. Copper shims of suitable size were provided in between the pump body and the engine frame, to vary the injection timing and its effect on the performance of the engine was studied, along with the change of injection pressures from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injection pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature (EGT) was measured with thermocouples made of iron and iron-constantan. Pollution levels of smoke and NO_x were recorded by AVL smoke meter and Netel Chromatograph NOx analyzer respectively at the peak load operation of the engine. Piezo electric transducer, fitted on the cylinder head to measure pressure in the combustion chamber was connected to a console, which in turn was connected to Pentium personal computer. TDC encoder provided at the extended shaft of the dynamometer was connected to the console to measure the crank angle of the engine. A special P-θ software package evaluated the combustion characteristics such as peak pressure (PP), time of occurrence of peak pressure (TOPP), maximum rate of pressure rise (MRPR) and time of occurrence of maximum rate of pressure rise (TOMRPR) from the signals of pressure and crank angle at the peak load operation of the engine. Pressure-crank angle diagram was obtained on the screen of the personal computer.



1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4.Orifice meter, 5.U-tube water manometer, 6.Air box, 7.Fuel tank, 8, Pre-heater, 9.Burette, 10. Exhaust gas temperature indicator, 11.AVL Smoke meter, 12.Netel Chromatograph NOx Analyzer, 13.Outlet jacket water temperature indicator, 14. Outlet-jacket water flow meter, 15.Piezo-electric pressure transducer, 16.Console, 17.TDC encoder, 18.Pentium Personal Computer and 19. Printer.

Fig.2 Experimental Set-up

3. RESULTS AND DISCUSSION

3.1 PERFORMANCE PARAMETERS

The variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in the conventional engine (CE) with WFVO, at various injection timings at an injection pressure of 190 bar, was shown in Fig.3. The variation of BTE with BMEP with pure diesel operation on CE at recommended injection timing was also shown for comparison purpose. CE with vegetable oil showed the deterioration in the performance for entire load range when compared with the pure diesel operation on CE at recommended injection timing. Although carbon accumulations on the nozzle tip might play a partial role for the general trends observed, the difference of viscosity between the diesel and vegetable oil provided a possible explanation for the deterioration in the performance of the engine with vegetable oil operation. In addition, less air entrainment by the fuel spay suggested that the fuel spray penetration might increase and resulted in more fuel reaching the combustion chamber walls. Furthermore droplet mean diameters (expressed as Sauter mean) are larger for vegetable oil leading to reduce the rate of heat release as compared with diesel fuel. This also, contributed the higher ignition (chemical) delay of the vegetable oil due to lower cetane number. According to the qualitative image of the combustion under the crude vegetable oil operation with CE, the lower BTE is attributed to the relatively retarded and lower heat release rates.

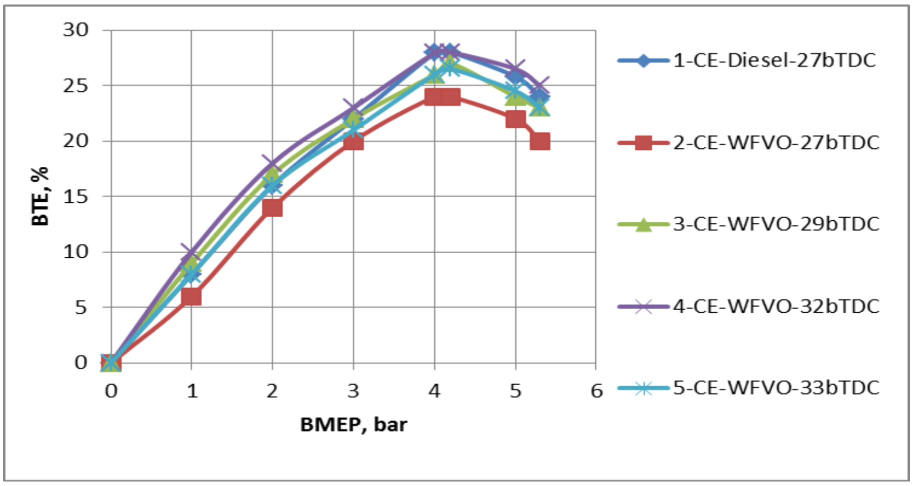


Fig.3 Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) in conventional engine (CE) at different injection timings with WFVO operation.

BTE increased with the advancing of the injection timing in CE with the vegetable oil at all loads, when compared with CE at the recommended injection timing and pressure. This was due to initiation of combustion at earlier period and efficient combustion with increase of air entrainment in fuel spray giving higher BTE. BTE increased at all loads when the injection timing was advanced to 32^{o}bTDC in the CE at the normal temperature of vegetable oil. The increase of BTE at optimum injection timing over the recommended injection timing with vegetable oil with CE could be attributed to its longer ignition delay and combustion duration. BTE increased at all loads when the injection timing was advanced to 32^{o}bTDC in CE, at the preheated temperature of WFVO. That, too, the performance was improved further in CE with the preheated vegetable oil for entire load range when compared with normal vegetable oil. Preheating of the vegetable oil reduced the viscosity, which improved the spray characteristics of the oil and reduced the impingement of the fuel spray on combustion chamber walls, causing efficient combustion thus improving BTE.

The variation of BTE with BMEP in the LHR engine with WFVO, at various injection timings at an injection pressure of 190 bar, was shown in Fig.4.

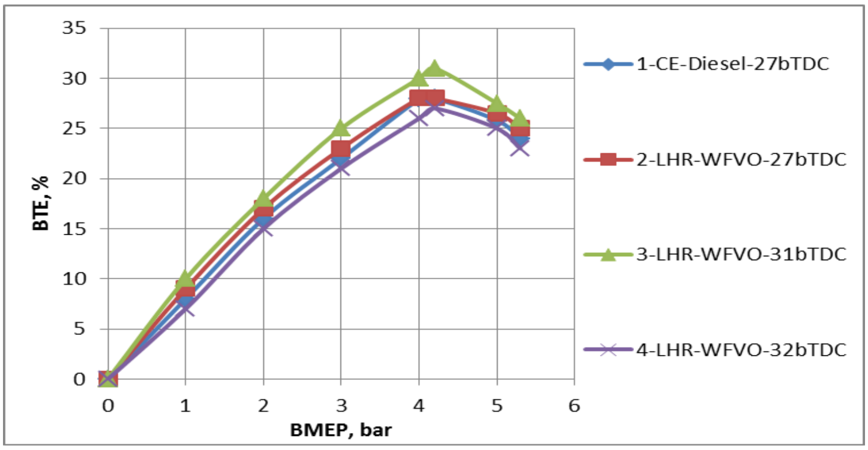


Fig.4 Variation of BTE with BMEP in LHR engine at different injection timings with WFVO

LHR version of the engine showed the marginal improvement in the performance for entire load range compared with CE with pure diesel operation. High cylinder temperatures helped in better evaporation and faster combustion of the fuel injected into the combustion chamber. Reduction of ignition delay of the vegetable oil in the hot environment of the LHR engine improved heat release rates and efficient energy utilization. Preheating of vegetable oil improves performance further in LHR version of the engine. The optimum injection timing was found to be 31^{o}bTDC with LHR engine with normal WFVO. Since the hot combustion chamber of LHR engine reduced ignition delay and combustion duration and hence the optimum injection timing was obtained earlier with LHR engine when compared with CE with the vegetable oil operation.

Injection pressure was varied from 190 bars to 270 bars to improve the spray characteristics and atomization of the vegetable oils and injection timing was advanced from 27 to 34°bTDC for CE and LHR engine. Table-1 showed the variation of BTE with injection pressure and injection timing at different operating conditions of WFVO with different configurations of the engine. BTE increased with increase in injection pressure in both versions of the engine at different operating conditions of the vegetable oil.

Table 1. Variation of peak bte with injection timing and injection pressure in CE and LHR engine at different operating conditions of the vegetable oil

Injection Timing (° bTDC)	Test Fuel	Peak BTE (%)											
		Conventional Engine (CE)						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	28	--	29	---	30	--	29	--	30	--	30.5	--
	WFVO	24	25	25	26	26	27	28	29	29	30	30	31
29	DF	28.5	--	29.5	--	30.2		29.5	--	30.5	--	31	--
	WFVO	25	26	26	27	27	28	29.5	30	30	30.5	30.5	31
30	DF	29	---	30	--	30.5	--	29	--	30	--	30.5	--
	WFVO	26	27	27	28	28	29	30	30.5	30.5	31	31.5	32
31	DF	29.5	--	30	--	31	--	--	--	--	--	--	--
	WFVO	27	28	28	29	29	30	31	31	32	32	33	33.5
32	DF	30		30.5		30.5							
	WFVO	28	29	29	30	30	31	--	--	--	--	--	--
33	DF	31		31		30	---	--	--	--	--	--	-

DF-Diesel Fuel, WFVO- Waste fried vegetable oil, NT- Normal or Room Temperature , PT- Preheat Temperature

The improvement in BTE at higher injection pressure was due to improved fuel spray characteristics. However, the optimum injection timing was not varied even at higher injection pressure with LHR engine, unlike the CE. Hence it was concluded that the optimum injection timing was 32°bTDC at 190 bar, 31°bTDC at 230 bar and 30°bTDC at 270 bar for CE. The optimum injection timing for LHR engine was 31°bTDC irrespective of injection pressure. Peak BTE was higher in LHR engine when compared with CE with different operating conditions of the vegetable oils.

Fig.5 showed the variation of the exhaust gas temperature (EGT) with BMEP in CE and LHR engine with WFVO at normal temperature at the recommended and optimized injection timings at an injection pressure of 190 bar. CE with WFVO at the recommended injection timing recorded higher EGT at all loads compared with CE with pure diesel operation. Lower heat release rates and retarded heat release associated with high specific energy consumption caused increase in EGT in CE. Ignition delay in the CE with different operating conditions of vegetable oil increased the duration of the burning phase. LHR engine recorded lower value of EGT when compared with CE with vegetable oil operation.

This was due to reduction of ignition delay in the hot environment with the provision of the insulation in the LHR engine, which caused the gases expanded in the cylinder giving higher work output and lower heat rejection. This showed that the performance was improved with LHR engine over CE with vegetable oil operation.

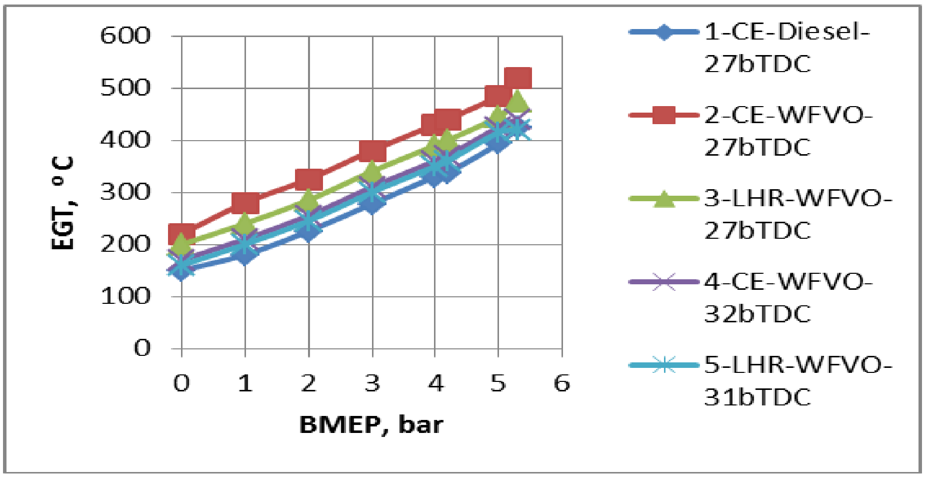


Fig.5 Variation of exhaust gas temperature (EGT) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with WFVO operation.

The magnitude of EGT at peak load decreased with advancing of injection timing and with increase of injection pressure in both versions of the engine with vegetable oil. Preheating of the vegetable oil further reduced the magnitude of EGT, compared with normal vegetable oil in both versions of the engine.

Table-2 showed the variation of EGT with injection pressure and injection timing at different operating conditions of WFVO with different configurations of the engine. EGT decreased with increase in injection pressure and injection timing with both versions of the engine, which confirmed that performance increased with increase of injection pressure. Preheating of vegetable oil decreased EGT in both versions of the engine.

Fig.6 showed the variation of the volumetric efficiency (VE) with BMEP in CE and LHR engine with WFVO at the recommended and optimized injection timings at an injection pressure of 190 bar. VE decreased with an increase of BMEP in both versions of the engine. This was due to increase of gas temperature with the load. At the recommended injection timing, VE in the both versions of the engine with WFVO operation decreased at all loads when compared with CE with pure diesel operation. This was due increase of temperature of incoming charge in the hot environment created with the provision of insulation, causing reduction in the density and hence the quantity of air with LHR engine. VE increased marginally in CE and LHR engine at optimized injection timings when compared with recommended injection timings with WFVO. This was due to decrease of un-burnt fuel fraction in the cylinder leading to increase in VE in CE and reduction of gas temperatures with LHR engine.

Table-4 showed the variation of VE with injection pressure and injection timing at different operating conditions of WFVO with different configurations of the engine.

VE increased marginally with the advancing of the injection timing and with the increase of injection pressure in both versions of the engine. This was due to better fuel spray characteristics and evaporation at higher injection pressures leading to marginal increase of VE. This was also due to the reduction of residual fraction of the fuel, with the increase of injection pressure. Preheating of the vegetable oil marginally improved VE in both versions of the engine, because of reduction of un-burnt fuel concentration with efficient combustion, when compared with the normal temperature of oil.

Table 2. The variation of egt at the peak load with the injection timing and injection pressure in the CE and LHR engine, at different operating conditions of the vegetable oil

Injection timing (^{o} b TDC)	Test Fuel	EGT at the peak load (^{o}C)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	425	--	410	---	395	--	460	---	450	--	440	--
	WFVO	520	500	500	490	490	465	470	450	450	430	430	410
29	DF							440		430		420	
	WFVO							430	410	410	390	390	370
30	DF	410	---	400	--	385	---	460	---	450	--	440	--
	WFVO	510	490	490	480	440	420	470	450	450	430	430	410
31	DF	400	---	390	--	375	---	450	---	445	---	440	---
	WFVO	450	415	440	425	435	435	420	400	400	380	380	360
32	DF	390		380		380							--
	WFVO	440	420	420	400	410	380	-------	---	---	----	---	-
33	DF	375	---	375	---	400	--	--	--	--	---	--	--

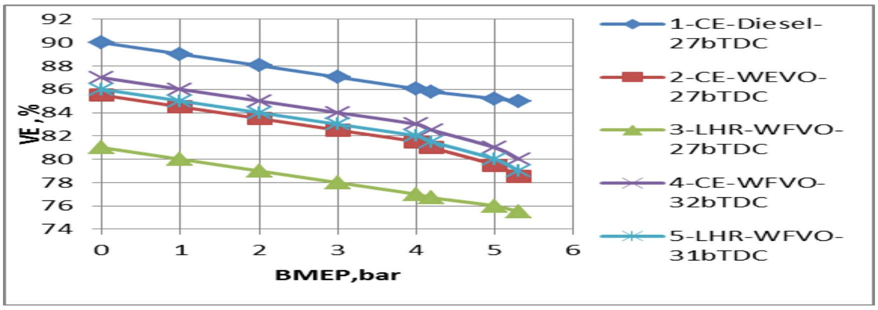


Fig.6. Variation of volumetric efficiency (VE) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with WFVO operation.

Table-4
Variation of volumetric efficiency (VE) at the peak load with the injection timing and injection pressure in the CE and LHR engine, at different operating conditions of the vegetable oil

Injection timing (°bTDC)	Test Fuel	Volumetric efficiency (%)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	85	--	86	--	87	--	78	--	80	--	82	--
	WFVO	78.5	79.5	79.5	80.5	80.5	81.5	75.5	76.5	76.5	77.5	77.5	78.5
29	DF							78.5		80.5		82.5	
	WFVO	80	81	81	82	82	83	77	77.5	78.5	79.5	79.5	80.5
30	DF	86	--	87	--	88	---	76	--	77	--	78	--
	WFVO	79	80	80	81	81	82	78	78.5	78.5	79	79	79.5
31	DF	87	--	87.5	--	89	--						
	WFVO	79.5	80.5	80.5	81.5	81.5	82.5	79	79.5	79.5	80	80	80.5
32	DF	87.5	--	88	--	87	--	-	--	-	--	--	-
	WFVO	80	81	81	82	82	83	--	--	--	--	--	--
33	DF	89	--	89	--	86	--	--	--	--	--	--	--

3.2 Pollution Levels

Fig.6 showed the variation of the smoke levels with BMEP in CE and LHR engine with vegetable oil operation at the recommended and optimized injection timings at an injection pressure of 190 bar.

Drastic increase of smoke levels was observed at the peak load operation in CE at different operating conditions of the vegetable oil, compared with pure diesel operation on CE. This was due to the higher magnitude of the ratio of C/H of WFVO (1.13) when compared with pure diesel (0.45). The increase of smoke levels was also due to decrease of air-fuel ratios and VE with vegetable oil compared with pure diesel operation. Smoke levels were related to the density of the fuel. Since vegetable oil has higher density compared to diesel fuels, smoke levels were higher with vegetable oil. However, LHR engine marginally reduced smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR engine at different operating conditions of the vegetable oil compared with the CE. Density influences the fuel injection system. Decreasing the fuel density tends to increase spray dispersion and spray penetration. Preheating of the vegetable oils reduced smoke levels in both versions of the engine, when compared with normal temperature of the vegetable oil. This was due to i) the reduction of density of the vegetable oils, as density was directly proportional to smoke levels, ii) the reduction of the diffusion combustion proportion in CE with the preheated vegetable oil, iii) the reduction of the viscosity of the vegetable oil, with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber.

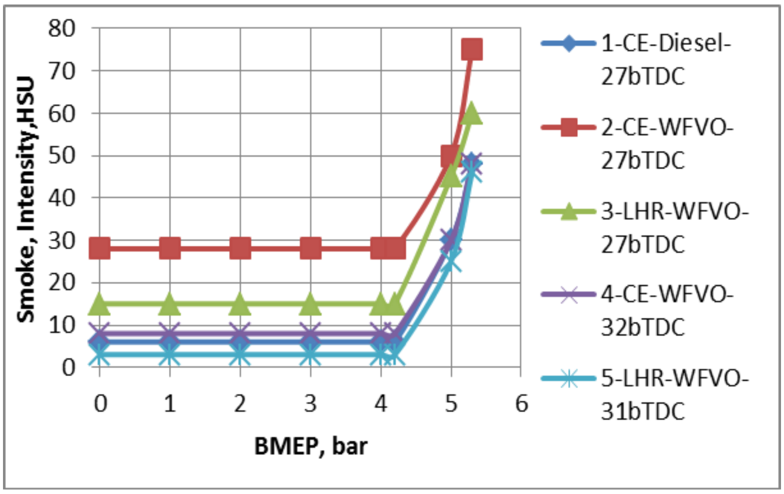


Fig.6. Variation of smoke intensity in Hartridge Smoke Unit (HSU) with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with crude WFVO

Table-5 showed the variation of smoke levels with injection pressure and injection timing at different operating conditions of WFVO with different configurations of the engine. Smoke levels decreased with increase of injection timings and with increase of injection pressure, in both versions of the engine, with different operating conditions of the vegetable oil. This was due to improvement in the fuel spray characteristics at higher injection pressures and increase of air entrainment, at the advanced injection timings, causing lower smoke levels.

Table 5. Variation of smoke intensity at the peak load operation with the injection timing and injection pressure in the CE and LHR engine, at different operating conditions of the vegetable oil

Injection timing (^{o}bTDC)	Test Fuel	Smoke intensity (HSU)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	48	--	38	--	34	--	55	--	50	--	45	--
	WFVO	75	65	65	60	63	60	60	45	45	40	40	35
29	DF	40	--	36	--	34							
	WFVO	68	64	63	59	60	57	47	40	40	35	35	30
30	DF	36	--	34	--	32	--	45	--	42	--	41	--
	WFVO	67	64	60	57	61	58	57	50	50	45	45	40
31	DF	33	---	32	--	30	--	43	--	41	--	40	--
	WFVO	60	57	57	54	54	60	46	40	40	35	35	30
32	DF	32	--	31	--	32	--	--	--	--	---	--	--
	WFVO	48	45	45	40	40	35	--	--	--	--	---	-
33	DF	30	---	30	--	35	--	-	--	--	--	--	--

Fig.7 showed the variation of the NOx levels with BMEP in CE and LHR engine with vegetable oil at the recommended and optimized injection timings at an injection pressure of 190 bar. NOx levels were lower in CE while they were higher in LHR engine at different operating conditions of the vegetable oil at the peak load when compared with diesel operation. This was due to lower heat release rate because of high duration of combustion causing lower gas temperatures with the vegetable oil operation on CE, which reduced NOx levels. Increase of combustion temperatures with the faster combustion and improved heat release rates in LHR engine caused higher NOx levels. As expected, preheating of the vegetable oil decreased NOx levels in both versions of the engine when compared with the normal vegetable oil. This was due to improved air fuel ratios and decrease of combustion temperatures leading to decrease NOx emissions in the CE and decrease of combustion temperatures in the LHR engine with the improvement in air-fuel ratios leading to decrease NOx levels in LHR engine.

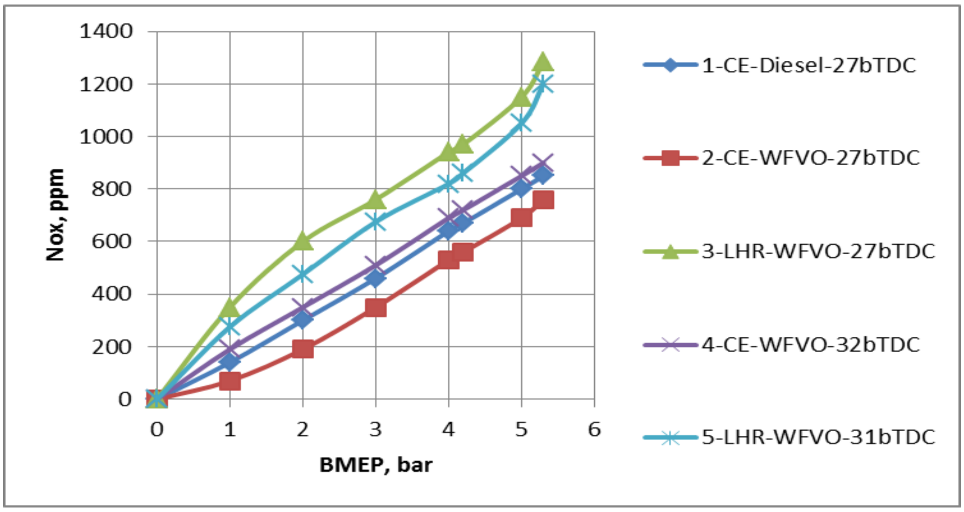


Fig.7. Variation of NOx levels with BMEP in CE and LHR engine at recommend injection timing and optimized injection timings with crude WFVO operation.

Table-6 showed the variation of NOx levels with injection pressure and injection timing at different operating conditions of WFVO with different configurations of the engine. NOx levels increased with the advancing of the injection timing in CE with different operating conditions of vegetable oil. Residence time and availability of oxygen had increased, when the injection timing was advanced with the vegetable oil operation, which caused higher NOx levels in CE. However, NOx levels decreased with increase of injection pressure in CE. With the increase of injection pressure, fuel droplets penetrate and find oxygen counterpart easily. Turbulence of the fuel spray increased the spread of the droplets which caused decrease of gas temperatures marginally thus leading to decrease in NOx levels. Marginal decrease of NOx levels was observed in LHR engine, due to decrease of combustion temperatures**,** which was evident from the fact that thermal efficiency was increased in LHR engine due to the reason sensible gas energy was converted into actual work in LHR engine, when the injection timing was advanced and with increase of injection pressure**.**

3.3 Combustion Characteristics

Table-7 presented the comparison on the magnitudes of PP, MRPR, TOPP and TOMRPR with the injection timing and injection pressure, at the peak load operation of CE and LHR engine with vegetable oil operation. Peak pressures were lower in CE while they were higher in LHR engine at the recommended injection timing and pressure, when compared with pure diesel operation on CE. This was due to increase of ignition delay, as vegetable oils require large duration of combustion. Mean while the piston started making downward motion thus increasing volume when the combustion takes place in CE. LHR engine increased the mass-burning rate of the fuel in the hot environment leading to produce higher peak pressures. The advantage of using LHR engine for vegetable oil was obvious as it could burn low cetane and high viscous fuels. Peak pressures increased with the increase of injection pressure and with the advancing of the injection timing in both versions of the engine, with the vegetable oil operation. Higher injection pressure produced smaller fuel particles with low surface to volume ratio, giving rise to higher PP. With the advancing of the injection timing to the optimum value with the CE, more amount of the fuel accumulated in the combustion chamber due to increase of ignition delay as the fuel spray found the air at lower pressure and temperature in the combustion chamber. When the fuel- air mixture burns, it produces more combustion temperatures and pressures due to increase of the mass of the fuel. With LHR engine, peak pressures increases due to effective utilization of the charge with the advancing of the injection timing to the optimum value. The magnitude of TOPP decreased with the advancing of the injection timing and with increase of injection pressure in both versions of the engine, at different operating conditions of vegetable oils. TOPP was more with different operating conditions of vegetable oils in CE, when compared with pure diesel operation on CE. This was due to higher ignition delay with the vegetable oil when compared with pure diesel fuel. This once again established the fact by observing lower peak pressures and higher TOPP, that CE with vegetable oil operation showed the deterioration in the performance when compared with pure diesel operation on CE. Preheating of the vegetable oil showed lower TOPP, compared with vegetable oil at normal temperature. This once again confirmed by observing the lower TOPP and higher PP, the performance of the both versions of the engine improved with the preheated vegetable oil compared with the normal vegetable oil.

Table 6. Variation of no_x levels at the peak load with the injection timing and injection pressure in CE and LHR engine at different operating conditions of the vegetable oil

Injection timing (° b TDC)	Test Fuel	NOx levels (ppm)											
		CE						LHR Engine					
		Injection Pressure (Bar)						Injection Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27	DF	850	----	810	----	770	---	1300	--	1280	--	1260	--
	WFVO	760	720	720	680	680	640	1285	1270	1255	1240	1220	1200
29	DF	900	--	860	--	820	--						
	WFVO	780	740	740	700	700	660	1210	1190	1190	1160	1160	1140
30	DF	935	---	900	---	860	--	1225	--	1205	--	1185	--
	WFVO	810	770	790	750	750	710	1260	1230	1230	1210	1210	1180
31	DF	1020	---	980	---	940	---	1150	--	1130	--	1110	--
	WFVO	860	820	820	780	780	740	1200	1180	1180	1140	1140	1100

32	DF	1105	----	1060	---	1020	---	--	--	--	--	--	--
	WFVO	900	860	860	820	820	780	--	-	--	--	--	-
33	DF	1190	----	1150	---	1110	---	--	--	--	--	--	-

Table 7. Variation of PP, MRPR, TOPP and TOMRPR with injection timing and injection pressure at the peak load operation on CE and LHR engine with vegetable oil operation

Injection timing (°bTDC)/ Test fuel	Engine version	PP(bar)				MRPR (Bar/deg)				TOPP (Deg)				TOMRPR (Deg)			
		Injection pressure (Bar)				Injection pressure (Bar)				Injection pressure (Bar)				Injection pressure (Bar)			
		190		270		190		270		190		270		190		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27/Diesel	CE	50.4	--	53.5	---	3.1	---	3.4	--	9	-	8	--	0	0	0	0
	LHR	48.1	--	53.0	--	2.9	--	3.1	--	10	--	9	--	0	0	0	0
27/ WFVO	CE	44.9	48.9	47.1	48.4	2.0	2.1	2.7	2.8	12	11	12	10	1	1	1	1
	LHR	57.8	58.7	61.1	62.8	3.1	3.2	3.3	3.4	11	10	10	9	1	1	1	1
31/WFVO	LHR	60.5	61.8	63.3	63.8	3.5	3.7	3.7	3.8	10	9	9	9	0	0	0	0
32/WFVO	CE	51.3	52.6			3.3	3.5			11	10			0	0		

This trend of increase of MRPR and decrease of TOMRPR indicated better and faster energy substitution and utilization by vegetable oils, which could replace 100% diesel fuel. However, these combustion characters were within the limits hence the vegetable oils could be effectively substituted for diesel fuel

4. CONCLUSIONS

Vegetable oil operation at 27°bTDC on CE showed the deterioration in the performance, while LHR engine showed improved performance, when compared with pure diesel operation on CE. Preheating of the vegetable oils improved performance when compared with normal vegetable oils in both versions of the engine. Improvement in the performance was observed with the advancing of the injection timing and with the increase of injection pressure with the vegetable oil operation on both versions of the engine. CE with crude vegetable oil operation showed the optimum injection timing at 32°bTDC, while the LHR engine showed the optimum injection at 31° bTDC at an injection pressure of 190 bars. At the recommended injection timing and pressure, crude vegetable oil operation on CE increased smoke levels, decreased NOx levels, while LHR engine decreased smoke levels and increased NOx levels when compared with pure diesel operation on CE. Preheating of the crude vegetable oil decreased smoke levels and NOx levels slightly in both versions of the engine. CE with vegetable oil operation decreased smoke levels and increased NOx levels, while LHR engine decreased smoke and NOx levels with the advancing of the injection timing. With increase in injection pressure, smoke an NOx levels decreased in both versions of the engine. Lower peak pressures and more TOPP were observed with normal crude vegetable oil in CE. LHR engine with vegetable oil operation increased PP and decreased TOPP when compared with CE. Preheating increased PP and decreased TOPP when compared with normal vegetable oil operation on both versions of the engine. Lower peak pressures were predicted in CE, while higher peak pressures in the LHR engine with crude vegetable oil operation at the recommended injection timing and pressure.

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