INVESTIGATIONS ON LOW HEAT REJECTION DIESEL ENGINE WITH CARBURETED ALCOHOLS AND CRUDE COTTONSEED OIL

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ABSTRACT

Alcohols and vegetable oils are promising fuels for replacing conventional diesel fuel. The advantages of alcohol (more volatility, low carbon to hydrogen ratio) and vegetable oils (comparable calorific value and cetane number) are attracting features to use them as substituted fuels in diesel engines. However demerits of alcohol (low calorific value and low cetane number (measure of combustion quality in diesel engines)) and vegetable oils (high viscosity and low volatility) call for low heat rejection (LHR) engine which has high heat release rate and faster rate of combustion. Heat flow to the coolant is minimized by providing thermal insulation in the path of heat flow to the coolant. Investigations were carried out to study the exhaust emissions from high grade low heat rejection (LHR) diesel engine consisting of air gap insulated piston with 3-mm air gap with superni (an alloy of nickel) crown, air gap insulated liner with superni insert and ceramic coated cylinder head with normal temperature condition of crude cottonseed oil and carbureted alcohol (methanol/butanol) with varied injection pressure and compared with methanol operation over butanol operation and also with net diesel operation on conventional engine (CE). Exhaust emissions of particulate matter and oxides of nitrogen (NO_x) were recorded by AVL Smoke meter and Netel Chromatograph NO_x analyzer respectively at full load operation of the engine. Aldehydes were measured by dinitrophenyl hydrazine (DNPH) method at full load operation of the engine. Particulate levels and NO_x levels decreased by 92% and 12% respectively with LHR engine at recommended injection timing of 27°bTDC (before top dead centre) and at an injection pressure of 190 bar with methanol operation in comparison with neat diesel operation on CE.

Keywords: Crude Vegetable Oil, Methanol, butanol, CE, LHR engine, Emissions.

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1. INTRODUCTION

Following fuel crisis and vehicular population growth, search for renewable and alternate fuels has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. Vegetable oils, which are renewable have properties compatible to diesel fuels. Hence these fuels (straight vegetable oils, SVO) can be directly substituted in diesel engines without the modification of the engine. However, higher viscosity and chemical composition of unprocessed vegetable oils and fats have been shown [1] to cause problems in a number of areas (i) piston ring sticking; (ii) injector and combustion chamber deposits; (iii) fuel system deposits; (iv) reduced power; (v) reduced fuel economy and (vi) increased exhaust emissions due to high value of C/H ratio (C= Number of carbon atoms, H= Number of hydrogen atoms in fuel composition).

Rudolph Diesel, the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. [2]. Several researchers experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the above mentioned problems of high viscosity, low volatility and their polyunsaturated character. Bio-diesels derived from vegetable oils present a very promising alternative to diesel fuel since biodiesels have numerous advantages compared to fossil fuels as they are renewable, biodegradable, provide energy security and foreign exchange savings besides addressing environmental concerns and socio-economic issues.[3-7]. Experiments were carried out with bio-diesel on CE and reported performance was comparable with pure diesel operation on CE.[8-12].

On the other hand alcohols are renewable and volatile fuels. There are many methods of inducting alcohols in diesel engines, out of which carburetion technique is simple one. Alcohol was inducted through a variable jet carburetor, installed in inlet manifold and diesel was injected in conventional manner. Investigations were carried out with carbureted alcohol and diesel on CE and reported that exhaust emissions of particulate matter and NO_x decreased in comparison with pure diesel operation on CE. [13-16]. However, alcohols have low cetane number (quality of combustion in diesel engine). Hence engine modification was necessary if alcohol was used as fuel in diesel engine. The drawbacks of the crude vegetable oil, biodiesel and alcohol call for hot combustion chamber provided by LHR diesel engine.

The major concept of LHR engine is to reduce heat loss to the coolant, by providing thermal insulation in the path of heat flow to the coolant. LHR engines were classified depending on degree of insulation, such as low grade, medium grade and high grade engines. In low grade LHR engines, ceramic coatings were provided on piston, liner and cylinder head while in medium grade LHR engines, air gap was created in the piston and other components with low-thermal conductivity materials like supuni, cast iron and mild steel etc. High grade LHR engines were the combination of low grade and medium grade.

Investigations were carried out by various researchers on low grade LHR ceramic coated diesel engines with pure diesel operation and reported that pollution levels of smoke decreased by 15% with ceramic coated engine. [17-19]. Experiments were carried out with biodiesel in low grade LHR diesel engine and reported that there was reduction of particulate matter and increase of NO_x levels. [20-23].

Creating an air gap in the piston involved the complications of joining two different metals like bolted and welded design adopted by researchers in fixing the crown of the piston to the body of the piston could not withstand more than 78 hours. [24]. Later it was a successful attempt of screwing the crown made of low thermal conductivity material, nimonic (an alloy of nickel) to the body of the piston, by keeping a gasket, made of nimonic, in between these two parts. [25]. It was reported from these investigations that smoke levels decreased by 12% at advanced injection timing of 29.5°bTDC.

Experiments were conducted on medium grade LHR engine which consisted of air gap insulated piston with superni crown and air gap insulated liner with superni insert with advanced injection timings and increased injection pressure with vegetable oils. [26-28]. They reported that particulate matter decreased by 20% and NO_x levels increased by 45% at peak load operation with LHR engine.

Experiments were carried out with high grade LHR engine, which consisted of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with vegetable oils [29-31]. They reported that LHR engine further increased NO_x levels and decreased smoke levels.

Alcohols, both ethanol and methanol were used in medium grade LHR engine along with vegetable oil [32-34]. They reported that particulate matter and NO_x emissions decreased considerably with LHR engine due to effect of higher heat generated in the combustion space due to adiabatic conditions improved alcohol combustion with varying pilot quantities of diesel. Vegetable oils have cetane number comparable with diesel fuel, but they have high viscosity and low volatility. Alcohols have low cetane fuels, though they have got high volatility. In order to take advantage from high cetane number and high volatility, both vegetable oils and alcohols can be used in LHR engine.

Particulate matter and NO_x are the emissions from diesel engine cause [35-37] health hazards like inhaling of these pollutants cause severe headache, asthma, bronchitis, emphysema, lung cancer, nausea, slowing down of reflexes, vomiting sensation, respiratory problems, skin cancer, hemorrhage, dizziness, drowsiness, etc. The contaminated air containing carbon dioxide released from automobiles reaches ocean in the form of acid rain, thereby polluting water. Hence control of these emissions is an immediate task and important.

As mentioned earlier, straight vegetable oil (SVO) cannot be used in diesel engines. Hence along with SVO, alcohol, which is volatile, was used in experiment. The present paper attempted to study exhaust emissions from high grade LHR engine, which contained air gap piston, air gap liner and ceramic coated cylinder head with crude cottonseed oil (CSO) with carbureted alcohol (methanol/ butanol) with varied injection pressure and compared with methanol operation with butanol operation on both versions of the engine and also with neat diesel operation on CE at 27°bTDC and at an injection pressure of 190 bar.

2. METHODOLOGY

Figure 1 shows the assembly details of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head. LHR diesel engine contained a two-part piston; the top crown made of low thermal conductivity material, superni-90 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 for improved performance of the engine with superni insert with diesel as fuel. [27]. 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. At 500°C the thermal conductivities of superni-90 and air are 20.92 and 0.057 W/m-K respectively. Partially stabilized zirconium (PSZ) of thickness 500 microns was coated by means of plasma coating technique.

The experimental setup used for the investigations of LHR diesel engine with cottonseed oil and carbureted alcohol is shown in Figure 1. CE had an aluminum alloy piston with a bore of 80 mm and a stroke of 110 mm. The rated output of the engine was 3.68 kW at a speed of 1500 rpm.

1.Engine, 2.Electical Dynamo meter, 3.Load Box, 4. Outlet jacket water temperature indicator, 5.Outlet-jacket water flow meter Orifice meter, 6. Piezo-electric pressure transducer, 7. TDC encoder 8.Console, 9. Pentium Personal Computer, 10. Printer, 11.Exhaust gas temperature indicator, 12.AVL Smoke meter, 13. Netel Chromatograph NO_x Analyzer, 14. Filter, 15.Rotometer, 16.Hetaer,17. Round bottom flask containing DNPH solution, 18.Burette, 19. Variable jet carburetor, 20. Air box, 21.Orifice meter, 22. U-tube water manometer, 23.Dieesl tank/vegetable oil tank, 24.Alcohol tank, 25. Three-way valve.

Figure 2 The Experimental Set-up

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 its brake power. Alcohol was inducted through the variable carburetor jet, located at the inlet manifold of the engine at different percentages of diesel flow rate by mass basis and crude vegetable oil (CSO) was injected in conventional manner. Two separate fuel tanks and burette arrangements were made for measuring vegetable oil and alcohol consumptions. 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 80°C by adjusting the water flow rate. The 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 emissions of particulate matter and NO_x were recorded by AVL smoke meter and Netel Chromatograph NO_x analyzer respectively at various values of BMEP. With alcohol-vegetable mixture operation, the major pollutant emitted from the engine is aldehydes. These aldehydes are carcinogenic in nature, which are harmful to human beings. The measure of the aldehydes is not sufficiently reported in the literature. DNPH method was employed for measuring aldehydes in the experiment. [32]. The exhaust of the engine was bubbled through 2,4 dinitrophenyl hydrazine (2,4 DNPH) solution. The hydrazones formed were extracted into chloroform and were analyzed by employing high performance liquid chromatography (HPLC) to find the percentage concentration of formaldehyde and acetaldehyde in the exhaust of the engine.

India with just 2.4% of the global area supports more than 16% of world's human population and 17% of the cattle population. According to economic survey (2010-2011), of the cultivable land area, about 250 million hectares are classified as waste and degraded or marginal land. If the non-forest waste-lands could be used to cultivate plants which can survive on such soil and which can produce oilseeds, these could be effectively used to combat fuels shortage in the country and at the same time bring such degrade lands back to its productive capacity. India is the second largest country to produce cottonseed oil. The whole seeds can be crushed to yield about 25% oil. Double crushing can increase the yield to 28.5% and solvent extraction to 30%. The properties of the diesel, vegetable oil, ethanol and methanol used in this work are presented in Table-1.

Table 1 Properties of test fuels

Test Fuel	Viscosity at 25°C (Centi-poise)	Density at 25°C	Cetane number	Calorific value (kJ/kg)
Diesel	12.5	0.84	55	42000
Crude cottonseed oil (CSO)	125	0.90	45	40000
Methanol	--	0.79	06	19700
Butanol	--	0.72	09	36700

3. RESULTS AND DISCUSSION

3.1. Performance Parameters

Investigations were carried out with the objective of determining the factors that would allow maximum use of alcohol in diesel engine with best possible efficiency at all loads.

Figure 2. Variation of brake thermal efficiency (BTE) with BMEP in CE.

Figure 2 indicates that BTE increased at all loads with 35% methanol (M) induction and with the increase of methanol induction beyond 35%, it decreased at all loads in CE when compared with CE with diesel operation (standard diesel). The reason for improving the efficiency with the 35% methanol induction was because of improved homogeneity of the mixture with the presence of methanol, decreased dissociated losses, specific heat losses and cooling losses due to lower combustion temperatures. This was also due to high heat of evaporation of methanol, which caused the reduction the gas temperatures resulting in a lower ratio of specific heats leading to more efficient conversion of heat into work. Induction of

methanol resulted in more moles of working gas, which caused high pressures in the cylinder. The observed increase in the ignition delay period would allow more time for fuel to vaporize before ignition started. This means higher burning rates resulted in more heat release rate at constant volume, which was a more efficient conversion process of heat into work. Similar observations were made with butanol also.

Fig.3 shows the variation of brake thermal efficiency with brake mean effective pressure of the engine in LHR engine with methanol induction. Curves from Figure 3 indicate that LHR engine showed an improvement in the performance with the carbureted methanol at all loads when compared to the standard diesel engine. This was due to recovery of heat from the hot insulated components of LHR engine due to high latent heat of evaporation of the methanol, which led to an increase in thermal efficiency. The maximum induction of methanol is 60% in LHR engine, which showed improvement in the performance at all loads when compared to standard diesel engine.

Figure 3. Variation of BTE with BMEP in LHR engine

However when the methanol induction was increased more than 60% in LHR engine, BTE is deteriorated at all loads when compared with standard diesel. This was due to increase of ignition delay. Butanol induction also followed similar trends in LHR engine. The maximum induction of butanol was found to be 60% in LHR engine.

3.2. Exhaust Emissions

Table 2 presents data of particulate matter at full load operation with induction of methanol and butanol with both versions of the engine. Particulate emissions were observed to be higher with LHR engine with pure diesel operation as it is noticed from Table.2 in comparison with neat diesel operation on CE. This was due to fuel cracking at higher temperature, leading to an increase in particulate matter. Higher temperature of LHR engine produced increased rates of both soot formation and burn up. The reduction in volumetric efficiency and air-fuel ratio were responsible factors for increasing particulate matter in the LHR engine near the peak load operation of the engine. As expected, particulate matter increased in the LHR engine because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion. Particulate matter increased drastically with CE with crude cottonseed oil (CSO) in comparison with neat diesel operation on CE. High density, high duration of combustion due to high viscosity and high value of C/H ratio in molecular composition of the

CSO were the reason of higher particulate matter with crude CSO. However, LHR engine with vegetable oil operation reduced particulate levels in comparison with CE with CSO operation. Faster rate of combustion, reduction of ignition delay and increased heat release rate reduced particulate levels with LHR engine with cottonseed oil operation.

Particulate matter decreased with induction of alcohol. The combustion of injected fuel in case of pure vegetable oil operation was predominantly one of oxidation of products of destructive decomposition. In this case, there were greater chances of fuel cracking and forming carbon particles. This was due to high calorific value of the diesel causing high combustion temperatures leading to produced higher NO_x levels. On the other hand, the combustion of alcohol was predominantly a process of hydroxylation and the chances of fuel cracking were negligible.

Methanol does not contain carbon-carbon bonds and therefore cannot form any un-oxidized carbon particles or precursor to soot particles. One of the promising factor for reducing particulate matter with the alcohols was they contained oxygen in their composition which helped to reduce soot density. Soot emissions increased linearly with the increase of carbon to hydrogen atoms (C/H) ratio provided the equivalence ratio was not altered. This is because higher C/H lead to more concentration of carbon dioxide, which would be further, reduced to carbon.

Table 2 Comparative data on particulate levels (Hartridge Smoke Unit) at full load operation

Injection timing (bTDC)	Test Fuel/ Engine Version	Alcohol induction on mass basis	Particulate levels at full load operation (HSU)					
			Methanol			Butanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
27	Diesel/CE	0%	48	40	34	48	40	34
	CSO/CE	0%	65	63	58	65	63	58
	CSO/LHR	0%	45	40	35	45	40	35
	Diesel/LHR	0%	60	55	50	60	55	50
	CE	35%	38	33	28	42	37	32
		40%	--	--	25	--	--	30
	LHR	60%	25	20	15	30	25	20

Consequently, induction of alcohol reduced the quantity of carbon particles in the exhaust gases as the values of C/H for diesel fuel, vegetable oil, methanol and butanol are 0.45, 0.83, 0.25 and 0.4 respectively. Lower particulate emissions at full load were observed in both versions of the engine in dual fuel mode when compared with neat diesel operation on CE. LHR engine with 60% methanol induction showed lower particulate emissions, when compared with CE with 35% methanol induction. Particulate levels decreased with the increase of methanol induction in both versions of the engine. In dual fuel operation, particulate matter further decreased with increase of injection pressure in both versions of the engine as it is noticed from the Table 2, due to efficient combustion at higher injection pressures, which improved the atomization hence faster rate of combustion and shorter combustion duration in both versions of the engine. Particulate levels were marginally lower with methanol operation in comparison with butanol operation in both versions of the engine as the value of C/H ratio of methanol (0.25) is lower than butanol (0.4).

The temperature and availability of oxygen are the reasons for the formation of NO_x . Table.3 shows data of nitrogen oxide (NO_x) levels at full load operation with different versions of the engine with test fuels. LHR engine with diesel operation increased NO_x levels drastically in comparison with CE with diesel operation. Improved heat release rate affected combustion

temperatures and thus increased NO_x levels with LHR engine with diesel operation. CE with crude vegetable oil operation reduced NO_x levels when compared with CE with neat diesel operation. As the fuel, CSO is high viscous, duration of combustion is high leading to produce lower combustion temperatures and thus lower NO_x levels.

From Table, it is noticed that NO_x emissions decreased with the increase of percentage of alcohol induction in both versions of the engine, due to lower combustion temperatures with the absorption of combustion temperatures with their high latent heat of evaporation of alcohols. The low value of C/H ratio in alcohols have indirect effect in reducing oxygen availability in the gases, which leads to the reduction of NO_x .

Table 3 Comparative data on NO_x levels at full load operation

Injection Timing (bTDC)	Test Fuel/ Engine Version	Alcohol induction on mass basis	NO _x at peak load operation (ppm)					
			Methanol			Butanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
27	Diesel/CE	0%	850	900	950	850	900	950
	CSO/CE	0%	675	725	775	675	725	775
	CSO/LHR	0%	1270	1230	1180	1270	1230	1180
	Diesel/LHR	0%	1300	1250	1200	1300	1250	1200
	CE	35%	425	475	525	475	525	575
		40%	--	--	475	--	--	525
	LHR	60%	750	700	650	800	750	700

However, LHR engine with different percentages of alcohol induction showed higher NO_x levels compared with CE with 35% methanol induction, due to increase of gas temperatures in LHR engine. However, they decreased with increase of injection pressure in LHR engine and increased with CE with test fuels because of increase of combustion temperatures in CE, while decrease of the same in LHR engine, as noticed from Table 3. NO_x levels were lower with methanol operation when compared with butanol operation on both versions of the engine. This was due to decrease of gas temperatures because of high latent heat of evaporation of methanol.

The aldehydes are responsible for pungent smell of the engine and affect the human beings when inhaled in the large quantities. The volatile aldehydes are eye and respiratory tract irritants. Though Government legislation has not been pronounced regarding the control of aldehyde emissions, when more and more alcohol engines are coming to existence severe measures the controlling of aldehydes emitted out through the exhaust of the alcohol run engines will have to be taken as serious view. It could be seen from the Table 4, that formaldehyde emissions were low with pure diesel operation in both CE and LHR engine.

Formaldehyde emissions increased drastically with methanol induction in both CE and LHR engine. With increased induction of methanol up to 60%, CE registered very high value of formaldehyde emissions in the exhaust, which showed the significant reduction in LHR engine. Hot environment of LHR engine completed combustion reactions and reduced the emissions of intermediate compounds, aldehydes. Hence it is concluded that LHR engine was more suitable for alcohol engines in comparison with pure diesel operation. However, formaldehyde emissions decreased with LHR engine in comparison with CE with the same amount of alcohol induction. This showed that LHR engine improved combustion and intermediate compounds were not formed during the combustion. Formaldehyde emissions were higher with methanol operation when compared with ethanol operation on both versions of the engine.

Table 4 Comparative data on Formaldehyde emissions at peak load operation

Injection timing (bTDC)	Test Fuel/ Engine Version	Alcohol induction on mass basis	Formaldehyde emissions at peak load operation (% concentration)					
			Methanol			Butanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
27	Diesel/CE	0%	5.5	5.0	4.5	5.5	5.0	4.5
	CSO/CE	0%	12.5	11.2	9.5	12.5	11.2	9.5
	CSO/ LHR	0%	10.5	9.3	7.5	10.5	9.3	7.5
	Diesel/LHR	0%	8.0	7.5	7.0	8.0	7.5	7.0
	CE	35%	28.3	26.2	24.1	18.3	16.3	14.2
		40%	--	--	26.4	--	--	16.4
	LHR	60%	30.2	28.2	26.6	24.3	22.1	20.4

Table.5 shows the data of acetaldehyde emissions at full load with varied injection pressure with both versions of the engine with test fuels. Table 5 followed the similar trend with Table 4. LHR engine decreased acetaldehyde emissions in comparison with CE with the same amount of alcohol induction. This was due to improved combustion in LHR engine because of high evaporation rate with the hot environment provided with LHR engine leading to reduce fuel deposits. Acetaldehyde emissions increased with increase of injection pressure in both versions of the engine at various percentages of alcohol induction. From the Table, it is noticed that, acetaldehyde emissions were higher with butanol operation in comparison with methanol operation in both versions of the engine at various percentage induction of alcohol. This was due to presence of more number of carbon atoms. .

Table 5 Comparative data on Acetaldehyde emissions at peak load operation

Injection Timing (bTDC)	Test Fuel/ Engine Version	Alcohol induction on mass basis	Acetaldehyde emissions at peak load operation (% concentration)					
			Methanol			Butanol		
			Injection pressure (bar)			Injection pressure (bar)		
			190	230	270	190	230	270
27	Diesel/CE	0%	7	6.5	6.0	7	6.5	6.0
	CSO/CE	0%	9	8	6.9	9	8	6.9
	CSO/LHR	0%	8	7	5.7	8	7	5.7
	Diesel/LHR	0%	10	9.5	9.0	10	9.5	9.0
	CE	35%	18.3	16.4	14.7	28.3	26.5	24.5
		40%	--	--	16.5	--	--	26.7
	LHR	60%	24.3	22.7	20.5	30.2	28.6	26.6

4. CONCLUSIONS

The maximum induction of alcohol (ethanol/butanol) was 35% with conventional engine, while it was 60% with LHR engine. Particulate levels at full load decreased by 34%, NO_x levels at peak load increased by 76%, Aldehyde emissions decreased in LHR engine when compared with CE with methanol operation.

Butanol operation followed similar trends with methanol operation. However, methanol operation reduced pollutants more effectively than butanol operation on both versions of the engine. Increase of injection pressure decreased pollutants with test fuels.

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