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Investigations on exhaust emissions of aninsulated diesel engine with alternative fuels

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ABSTRACT

In the context of depletion of fossil fuels, ever increase of pollution levels with fossil fuels and escalating prices of crude petroleum in International market, the search for alternative fuels has become pertinent. Alcohols (ethanol, methanol and butanol) and vegetable oils are important substitutes for diesel fuel. Alcohols renewable in nature, have low C/H (C=Number of carbon atoms and H=Number of hydrogen atoms in fuel composition and highly volatile. Butanol has higher calorific value than ethanol and methanol. Vegetable oils comparable cetane number and energy content when compared to diesel fuel. However, the drawbacks of vegetable oils (high viscosity and low volatility) and alcohols (low cetane number and low energy content) to be used as fuels in diesel engine call for semi adiabatic diesel engine (SADE) with its significance characteristics of higher operating temperature, maximum heat release, high brake thermal efficiency and ability to handle the low calorific value fuel.Exhaust emissions from diesel engine cause severe health hazards once they are inhaled in. They also cause environmental disorders. Hence control of these emissions is immediate step and urgent. In order to take advantages from both vegetable oils and alcohols, it is proposed to use the vegetable oil along with carbureted butanol in semi adiabatic diesel engine. Butanol was inducted into the engine through a variable jet carburetor, installed at the inlet manifold of the engine at different percentages of crude vegetable oil at full load operation on mass basis. Crude vegetable oil was injected at near end of compression stroke in conventional manner. Exhaust emissions were determined with semi adiabatic engine consisting of air gap (3 mm) insulated piston with superni (an alloy of nickel) crown, air gap (3 mm) insulated liner with superni insert and ceramic coated cylinder head with mixture of carbureted butanol and crude vegetable oil with varied injector opening pressure and injection timing. Comparative studies were made with data of conventional engine (CE) with maximum induction of butanol at similar operating conditions. Aldehydes were measured by wet method. The maximum induction of butanol was 60% at recommended injection timing of 27^{o}bTDC (before top dead center), while it was 55% at optimum injection timing of 29^{o}bTDC.

Key words: *Crude vegetable oil, Alcohol (ethanol, methanol and butanol), Semi adiabatic diesel engine, Fuel performance, Emissions and Combustion characteristics.*

Introduction

Increasing industrialization of developing countries is resulting in increased demand for diesel worldwide. Substitution of this demand with straight vegetable oils (SVOs) is comparatively environmentally benign compared to mineral diesel. Utilization of locally produced and processed fuel strengthens economy and energy security. Newer options of alternative fuels should be technically feasible, economically competitive, environment friendly and provide energy security without compromising the engine performance and emitting lesser quantity of harmful pollutant species (Bryant, 1976). Even Rudolf Diesel, the inventor of CI engine expressed the possibility of using vegetable oil as CI engine fuel during 1900 world exhibition in the Paris and demonstrated using peanut oil as fuel in his newly invented diesel engine ((Bryant, 1976). Several researchers experimented the use of vegetable oils as fuel on conventional engines (CE) and reported that the performance was poor, citing the problems of high viscosity, low volatility and their polyunsaturated character (Agarwal *et al.,* 2009; Agarwal *et al.,* 2010; Elango *et al.,* 2011; Soo-Young, 2011; Misra, 2010; Navindgi *et al.*, 2011; Navindgi *et al.,* 2012). The high viscosity of the vegetable oils cause problems in the injection process leading to an increase in particulate emissions and low volatility of the vegetable oils leads to oil sticking to the injector or combustion chamber walls resulting in deposit formation which interferes with the combustion. Increased injector opening pressures may also result in efficient combustion in compression ignition engine (Heywood, 1988; Jindal *et al.*, Venkanna, 2010; Agarwal *et al.*, 2013).

Butanol is preferable to methanol and ethanol for in diesel engines due to its greater heating value, higher cetane number and lower vapor pressures. Butanol is produced by thefermentation of biomass, resulting in lower cost of production and less corrosive. Furthermore, the carbon chain of butanol is twice that of methanol and ethanol, which implies that butanol has higher heating values and efficiency.

There are many methods of inducting alcohols in diesel engines, out of which blending is simple technique (Lalit Kumar Daheriya *et al.,* 2012; Wang *et al.,* 2008; Satish Kumar *et al.,* 2013). However, the maximum amount of induction of alcohol in compression ignition engine is limited in blending technique. Hence the carburetion technique of inducting alcohol in diesel engine is finding favor from various researchers from the point of view of effectiveness and operation. Alcohol was inducted through a variable jet carburetor, installed in inlet manifold of the engine and diesel was injected in conventional manner. Experiments were conducted with carbureted methanol/ethanol with injected biodiesel in conventional diesel engine (Hari Babu *et al.,* 2010; Rambabu *et al.,* 2010). They reported from their investigations that performance improved with carburetion technique. Exhaust emissions of particulate matter and nitrogen oxides (NO_x) decreased in comparison with neat diesel operation (DF) on conventional engine. However, butanol has a low cetane number. Hence engine modification is necessary if carbureted alcohol is used as fuel in diesel engine. The drawbacks associated with the crude vegetable oiland butanol as fuels in diesel engine call for hot combustion chamber provided by semi adiabatic diesel engine.

The concept of semi adiabatic diesel engine is to minimize heat loss to coolant by providing thermal insulation in the path of heat flow to the coolant. Two approaches that are being pursued to decrease heat rejection are (1) ceramic coating and (2) air gap insulation. Semi adiabatic diesel engines are classified based on degree of insulation, such as low grade, medium grade and high grade insulated engines. Low grade semi adiabatic diesel engine consists of ceramic coatings provided on engine components such as crown of the piston, inner side portion of the cylinder head and liner. Medium grade semi adiabatic diesel engine consists of two part piston-the top crown made of low thermal conductivity material is screwed to the aluminum body of the piston providing an air gap in between the crown and the body of the piston. An insert made of low thermal conductivity material is screwed to the top portion of the liner in such a manner that an air gap is maintained between the insert and liner body. High grade semi adiabatic diesel engine is combination of ceramic coated semi adiabatic diesel engine provided with air gap insulation.

Experiments were carried with high grade semi adiabatic diesel engine with vegetable oil operation Kesava Reddy *et al.,* 2012; Chowdary *et al.,* 2012; Janardhan *et al.,* 2013). They reported that performance deteriorated with CE with vegetable oil operation. Peak brake thermal efficiency increased by 4–5%, decreased particulate matter by 25–30% and increased NO_x emissions by 45–50% with high grade semi adiabatic diesel engine with vegetable oil operation in comparison with neat diesel operation on CE.

Alcohols (ethanol and methanol) were carbureted, while vegetable oil was injected in semi adiabatic diesel engine consisting of ceramic coated cylinder head with partially stabilized zirconium of thickness 500 microns coated on inside portion of cylinder head with varied injection timing and injector opening pressure (Murali Krishna *et al.,* 2015;

Murali Krishna *et al.*, 2014a; Murali Krishna *et al.*, 2014b). They reported from their studies that the maximum induction of alcohol (ethanol/methanol) was found to be 35% with CE, while it was 50% with engine with semi adiabatic diesel engine at recommended injection timing of 27^{o}b TDC on mass basis of vegetable oil at full load operation. Methanol was inducted through variable jet carburetor installed at inlet manifold of the semi adiabatic diesel engine consisting of air gap insulated piston with superni (an alloy of nickel) crown and air gap insulated liner with superni insert and crude jatropha oil was injected in conventional manner (Murali Krishna *et al.*, 2014a). The maximum induction of methanol was 55% at recommended injection timing, while for conventional engine it was 35% on mass basis. Semi adiabatic diesel engine with carbureted methanol improved the performance and reduced pollution levels in comparison with CE with carbureted methanol. Methanol/ethanol was inducted in semi adiabatic diesel engine consisting of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head and crude jatropha oil was injected in conventional manner (Murali Krishna *et al.*, 2014b). The maximum induction of alcohol (ethanol/methanol) was observed to be 35% with CE, while it was 60% for semi adiabatic diesel engine at recommended injection timing. With maximum induction of alcohol, at recommended injection timing and optimized injection timings, the performance of the semi adiabatic diesel engine improved performance when compared with CE. Methanol induction improved performance with semi adiabatic diesel engine, while ethanol induction showed improved performance with CE at recommended injection timing and optimized injection timing.

Vegetable oils have comparable cetane number and energy content with diesel fuel (DF). Butanol has high volatility and low C/H (C=Number of carbon atoms, H= Number of hydrogen atoms in fuel composition). In order to obtain maximum performance from engine with minimum pollution levels, the combination of carbureted butanol and crude vegetable oil as pilot fuel is to be attempted in compression ignition engine. No systematic studies on comparative performance of carbureted butanol with high grade semi adiabatic diesel engine, consisting of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head with varied injection timing and injector opening pressure was available.

An attempt was made here to evaluate the performance of the high grade semi adiabatic diesel engine, which contained air gap (3 mm) insulated piston with superni crown, air gap (3 mm) insulated liner with superni insertand ceramic coated cylinder head, fuelled with crude karanjaoil (CKO) and carbureted butanol with varied injector opening pressure and injection timing. Comparative studies were made with data of conventional engine with maximum induction of butanol, with varied engine parameters.

Materials and Methods

Fabrication of engine with LHR combustion chamber

Fig.1. shows assembly details of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head. High grade semi adiabatic diesel engine contained a two-part piston; the top portion, crown made of superni, a low thermal conductivity material (thermal conductivity of superni is $\frac{1}{16}$ of that of aluminum alloy of the piston) was screwed to aluminum alloy body of the piston, with 3mmair gap in between the crown and the body of the piston by providing gasket made of supernimaterial. An insert made of Superni 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. An air gap of 3 mm was found to be optimum by earlier researchers (Ramamohan *et al.*, 1999).

Partially stabilized zirconium (PSZ) of thickness 500 microns was coated over inside portion of cylin-

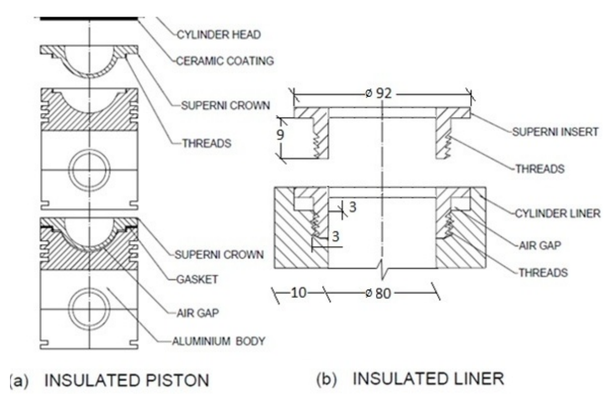


Fig. 1. Assembly details of air gap insulated piston, air gap insulated liner and ceramic coated cylinder head.

der head. The low thermal conductivities of superni, air and PSZ provided sufficient insulation for heat flow to the coolant.

Test fuels

Pongam is synonymous with karanji oil; the later is more common in trade and commercial circles (Murali Krishna, 2004). Karanja oil extracted from the seeds of tree, which belongs to the species pongamiaglabra vent. The yield of the kernels per tree is reported to vary between 8 kg and 24 kg. The kernels contain 27–39 percent of oil (Murali Krishna, 2004).

Manufacturing of butanol

Biobutanol can be produced by fermentation of biomass by the A.B.E. process. The process uses the bacterium *Clostridium acetobutylicum*, also known as the *Weizmann organism* (Heywood, 1988). The properties of test fuels were shown in Table 1.

Experimental setup

Fig. 2 shows the schematic diagram of the experimental setup used for the investigations on the high grade semi adiabatic diesel engine with karanja oil and carbureted butanol. The specifications of the experimental engine are shown in Table 2.

Table 3 shows different accuracy of instruments used in experiment. Dynamometer was loaded by a loading rheostat. The speed of the engine was measured with digital tachometer with accuracy ± 5 rpm. A variable jet carburetor was fitted at the inlet manifold of the engine for inducting butanol at different percentages at full load operation of vegetable oil on mass basis during the suction stroke of the engine. Crude karanja oil was injected into the engine through conventional injection system. Two separate fuel tanks and glass burette arrangements were made for measuring vegetable oil and butanol consumptions using stop watch. By pass arrangement was provided for the engine to run with either neat vegetable oil/diesel fuel or carbureted alcohol along with vegetable oil.

Air-consumption of the engine was obtained with an aid of air box, orifice flow meter and U-tube water manometer assembly. Air box with diaphragm was used to damp out the pulsations produced by the engine, for ensuring a steady flow of air through the intake manifold. The naturally aspirated engine was provided with water-cooling system in which

Table 1. Properties of Test Fuels

Test Fuel	Kinematic Viscosity at 40 ^oC (mm^2/s)	Specific gravity 15 ^oC	Cetane number	Low calorific value (kJ/kg)
Diesel (DF)	3.07	0.84	55	42000
Crude Karanja oil (CKO)	34.05	0.92	45	39000
Butanol	2.1	0.81	25	33480
ASTM Standard	ASTM D 445	ASTM D 4809	ASTM D 613	ASTM D 4809

Table 2. Specifications of the Test Engine

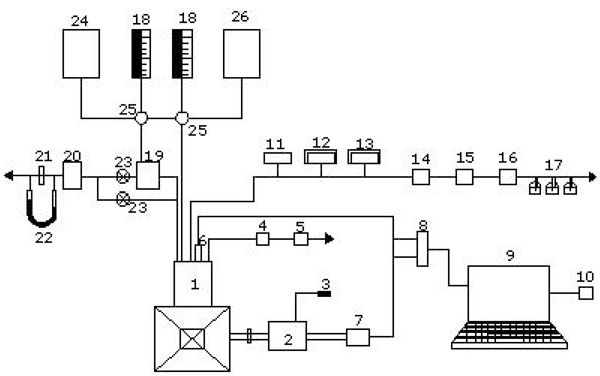
Description	Specification
Engine make and model	Kirloskar (India) AV1
Maximum power output at a speed of 1500 rpm	3.68 kW
Number of cylinders × cylinder position× stroke	One × Vertical position × four-stroke
Bore × stroke	80 mm × 110 mm
Dynamometer	Electrical (Kirloskar make)
Method of cooling	Water cooled
Rated speed (constant)	1500 rpm
Fuel injection system	In-line and direct injection
Compression ratio	16:1
BMEP @ 1500 rpm	5.31 bar
Manufacturer's recommended injection timing and pressure	27^{o}bTDC × 190 bar
Dynamometer	Electrical dynamometer
Number of holes of injector and size	Three × 0.25 mm
Type of combustion chamber	Direct injection type
Fuel injection nozzle	Make: MICO-BOSCHNo- 0431-202-120/HB

inlet temperature of water was maintained at 80 °C by adjusting the water flow rate. The water flow rate was measured by means of analogue water flow meter, with accuracy of measurement of ±1%. 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 injector opening pressure from 190 bar to 270 bar (in steps of 40 bar) using nozzle testing device. The maximum injector opening pressure was restricted to 270 bar due to practical difficulties involved. Exhaust gas temperature was measured by employing iron and iron-constantan thermocouples connected to a temperature indicator. The accuracy of analogue exhaust gas indicator is ± 5 °C.

Measurement of exhaust emissions

Particulate emission and nitrogen oxide (NO_x) emissions are the exhaust emissions from diesel engine. They create health hazards, when they are inhaled, which cause severe headache, tuberculosis, lung cancer, nausea, respiratory problems, dizziness, skin cancer and hemorrhage (Khopkar, 2010; Sharma, 2010). They contaminated air containing carbon dioxide released from automobiles reach ocean in the form of acid rain, there by polluting water. Hence control of these emissions is an immediate task and important.



1. Engine, 2. Electical Dynamometer, 3. Load Box, 4. Outlet jacket water temperature indicator, 5. Outlet-jacket water flow meter 6. Piezo-electric pressure transducer, 7. TDC encoder 8. Console, 9. Pentium Personal Computer, 10. Printer, 11. Exhaust gas temperature indicator, 12.AVL Particulate matter analyzer, 13. Netel Chromatograph NO_x Analyzer, 14. Filter, 15. Rotometer, 16. Heater, 17. Round bottom flask containing DNPH solution, 18. Burette, 19. Variable jet carburetor, 20. Air box, 21. Orifice flow meter, 22. U-tube water manometer, 23.By pass valve, 24. Alcohol tank, 25.Three-way valve, 26. Vegetable oil tank.

Fig. 2. Schematic diagram of the experimental set–up

Exhaust emissions of particulate matter and NO_x were recorded by AVLsmoke meter (AVL 437) and Netel Chromatograph NO_x analyzer (4000 VM) at full load operation of the engine. To ensure that accuracy of measured values was high, the gas analyzers were calibrated before each measurement using reference gases. The measuring principle, range and least count of these analyzers was given in Table 3.

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. (Inove To Kuta, Oishi Kiyohiko *et al.*, 1988). The exhaust of engine was filtered by means of filter and then heated up to 140 °C by means of heater provided in the circuit. A fixed quantity of exhaust (2l/m) measured by means of rotometer was bubbled through 2,4dinitrophenyl hydrazine (2,4 DNPH) solution. The hydrazones formed were extracted into chloroform and were analyzed by employing high performance liquid chromatography (HPLC) test to find the percentage concentration of formaldehyde and acetaldehyde in the exhaust of the engine. The advantage of this method was determination of both formaldehyde concentration and acetaldehyde concentration simultaneously in the exhaust of the engine.

Inove to Kuta, Oishi Kiyohiko

Determination of combustion characteristics

In-cylinder pressure was measured by a water-

Table 3. Specifications of the Smoke Opacimeter (AVL, India, 437) and exhaust gas emission analyzer (Netel Chromatograph NO_x Analyzer (4000 VM))

Pollutant	Measuring Principle	Range	Least Count	Repeatability
Smoke Opacity	Light extinction	1–100%	1% of Full Scale (FS)	1% for 30 minutes
NO_x	Chemiluminiscence	1–5,000 ppm	5 ppm	<0.1% range

cooled piezoelectric pressure transducer (AVL, Austria: QC34D). A precision shaft encoder (AVL, Austria: 365x) with a crank angle (CA) resolution of 0.5 crank angle degrees (CAD) is used for determining the crankshaft position. Combustion diagnosis was carried out with aid of miniature Piezo electric pressure transducer fitted on the cylinder head and TDC encoder fixed on the output shaft of the engine. The pressure and crank angle signals were fed to console from which pressure–crank angle diagram was obtained on the screen of Personal computer using a specialized software package. The accuracy of measurement of pressure is ± 1 bar, while it is ± 1° for crank angle.

Operating conditions

Test fuels used in the experimentation were crude karanja oil (CKO) and carbureted butanol with injected vegetable oil. Different injector opening pressures attempted in this experiment were 190, 230 and 270 bar. Various injection timings attempted in the investigations were 27–34° bTDC. The various versions of the engine were conventional engine and semi adiabatic diesel engine (SADE) consisting of air gap insulated piston with superni crown, air gap insulated liner with superni insert and ceramic coated cylinder head. Each test was repeated ten times to ensure the reproducibility of data according to the procedure adopted in error analysis. (Minimum number of trials must be not less than ten).

Results and Discussion

Performance parameters

Evaluated performance parameters were brake thermal efficiency, brake specific energy consumption, exhaust gas temperature, coolant load and volumetric efficiency.

Crude Vegetable oil Operation

The optimum injection timing with CE with crude karanja oil was 32° bTDC while it was 29° bTDC for high grade semi adiabatic diesel engine (Murali Krishna *et al.*, 2015). The hot combustion chamber of semi adiabatic diesel engine reduced ignition delay and combustion duration, hence the optimum injection timing was obtained earlier with semi adiabatic diesel engine, when compared with CE with the vegetable oil operation.

Carbureted Butanol and Injected Vegetable Oil Operation

Fig. 3. shows variation of brake thermal efficiency with brake mean effective pressure with conventional engine with different percentages of butanol induction.

From Fig. 3, it is noticed that up to 80% of full load, BTE increased at all load with test fuels and beyond 80% of full load it decreased. Increase of fuel conversion efficiency might have increased BTE up to 80% of the full load. Decrease of volumetric efficiency, oxygen-fuel ratio and mechanic efficiency might have lowered BTE with test fuels. From the same Fig, it is noticed that brake thermal efficiency increased at all loads with 35% butanol induction and with an increase of butanol induction beyond 35%, it decreased at all loads in CE when compared with CE with diesel operation. The reasons for improving thermal efficiency with the 35% butanol induction were improved homogeneity of the mixture with the presence of butanol, decreased dissociated losses, specific heat losses and cooling losses due to lower combustion temperatures. High heat of evaporation of butanol, which caused reduction in the gas temperatures resulting in a lower ratio of specific heats leading to more efficient conversion of heat into work, might be the reasons with improvement in the performance of the engine.

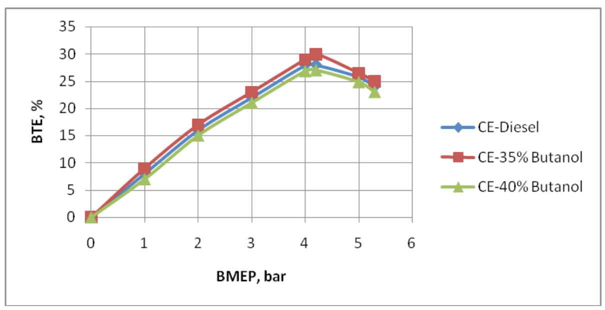


Fig. 3. Variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP)

Fig. 4 shows variation of brake thermal efficiency (BTE) with brake mean effective pressure (BMEP) with semi adiabatic diesel engine (SADE) with various percentages of butanol induction. Curves in Fig. 7 indicate that semi adiabatic diesel engine showed an improvement in the performance with the carbureted butanol at all loads when compared with the CEwith diesel operation. Recovery of heat from the hot insulated components of semi adiabatic diesel

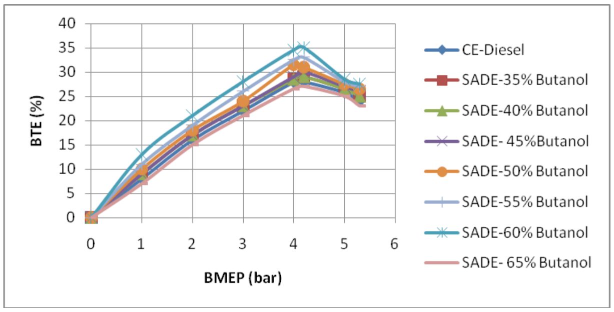


Fig. 4. Variation of brake thermal efficiency with brake mean effective pressure

engine due to high latent heat of evaporation of butanol might have improved the performance of the engine.

The maximum induction of butanol was 60% in semi adiabatic diesel engine, which showed improvement in the performance at all loads when compared with diesel operation on CE.However, maximum induction of butanol was limited to 55% in the semi adiabatic diesel engine at 29°bTDC against 60% induction at 27°bTDC,while maximum induction of butanol remained the same in CE at 32°bTDC as in the case of 27°bTDC. Reduction of gas temperatures at optimum injection timing might have absorbed low amount of butanol with semi adiabatic diesel engine. Similar trends were noticed with methanol induction by other researchers with high grade semi adiabatic diesel engine (Navindgi *et al.,* 2012).

Exhaust Emissions

Particulate emissions and nitrogen oxide levels are the exhaust emissions from compression ignition engine. These pollution levels were measured by sophisticated analyzers at full load operation of the engine. Fig. 5 shows histograms showing the variations of particulate emissions at full load different versions of the engine with maximum butanol induction at an injector opening pressure of 190 bar. In the same plot, variation of particulate emissions at full load for different versions of the engine with neat vegetable oil was also shown for the purpose of comparison. Particulate emissions decreased with advanced injection timing with test fuels with both versions of the engine. Improved atomization of fuel and initiation of combustion at early period might have reduced particulate emissions. CE with crude vegetable oil increased particulate emissions drastically in comparison with neat diesel operation on CE. Particulate emissions increases linearly with density of the fuel and increase of carbon to hydrogen atoms (C/H) ratio provided the equivalence ratio is not altered. This is because high value of C/H lead to more concentration of carbon dioxide, which would be further, reduced to carbon. Consequently, induction of butanol reduced the quantity of carbon particles in the exhaust gases as the value of C/H for diesel fuel and butanol are 0.45 and 0.40. CE with crude vegetable oil operation increased particulate emissions at full load operation. The combustion of injected fuel in case of vegetable oil operation is predominantly one of oxidation of products of destructive decomposition. In this case, there are greater chances of fuel cracking and forming carbon particles. C/H ratio for vegetable oil is 1.6 ($C_{19}H_{12}O_6$), while density is 0.91 against 0.44 ($C_{10}H_{22}$) and 0.84 for diesel. With maximum induction of butanol, semi adiabatic diesel engine (SADE) decreased particulate emissions by 14% at recommended injection timing and 14% at optimized injection timing in comparison with CE. High amount of butanol induction in semi adiabatic diesel engine (SADE) which caused improved combustion with reduction of fuel cracking temperatures with presence of oxygen in its fuel composition might have reduced particulate emissions. Increase of value of C/H ratio (C=Number of carbon atoms and H=Number of hydrogen atoms in fuel composition), increase of density of fuel (density is related to particulate emissions), presence of fatty acids and high viscosity coupled with retarded heat release rate might have increased particulate emissions with CE with vegetable oil operation.

However, when crude vegetable oil was injected, and butanol was carbureted, particulate emissions decreased with both versions of the engine. Reduction of gas temperatures thus eliminating fuel crack-

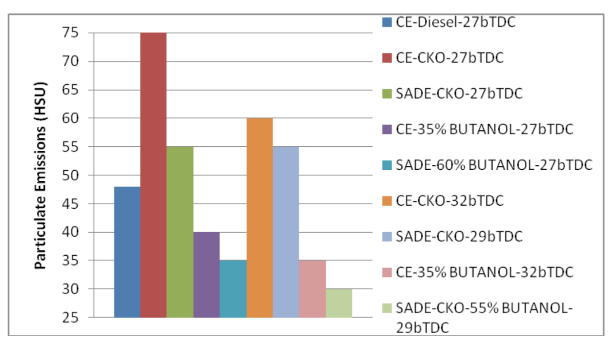


Fig. 5. Histograms showing the variation of particulate emissions in Hartridge Smoke Unit at full load

ing reactions caused reduction of particulate emissions with an increase of butanol induction. Supply of additional oxygen improved combustion reactions with induction of butanol. CE with maximum induction of butanol decreased particulate emissions at full load by 33% at recommended injection timing and 42% at optimum injection timing in comparison with CE with neat vegetable oil operation. Semi adiabatic diesel engine with maximum induction of butanol reduced particulate emission by 42% at recommended injection timing and 46% at optimum injection timing in comparison with semi adiabatic diesel engine with neat vegetable oil operation. Semi adiabatic diesel engine with maximum induction of butanol decreased particulate emission at full load by 12% at recommended injection timing and 14% at optimum injection timing in comparison with CE with maximum induction of butanol. High amount of butanol induction improved evaporation rate thus eliminating fuel cracking reactions causing reduction of particulate emissions at full load.

Table 4 shows data of particulate emissions and nitrogen oxide levels at full load which varied with injector opening pressure. From Table 6, it is evident that Particulate emissions decreased with an increase of butanol induction in both versions of the engine. Particulate emissions further decreased with an increase of injector opening pressure in both versions of the engine, as it is noticed from Table 6. Efficient combustion at higher injector opening pressures, which improved the atomization with the reduction of mean diameter of the fuel particle might have reduced particulate emissions. From Table 6, it is noticed that, at the optimum injection timing, semi adiabatic diesel engine (SADE) with test fuels recorded lower NO_x emissions, at full load operation compared to the same version of the engine at the recommended injection timing.

Decrease of combustion temperatures with improved oxygen–fuel ratios might have reduced NO_x emissions at full load. NO_x levels further decreased with an increase of butanol induction in both versions of the engine. Reduction of gas temperatures as butanol has high latent heat of evaporation might have reduced NO_x emissions. With maximum induction of butanol, semi adiabatic diesel engine increased NO_x emissions by 50% at recommended injection timing and 60% at optimum injection timing in comparison with CE

Fig. 6 shows histograms showing the variations of nitrogen oxide (NO_x) levels at full load different versions of the engine with maximum butanol induction at an injector opening pressure of 190 bar. In the same plot, variation of nitrogen oxide levels at full load for different versions of the engine with neat vegetable oil was also shown for the purpose of comparison. NO_x levels increased with CE, while they decreased for semi adiabatic diesel engine with advanced injection timing. Increase of resident timing and gas temperatures might have increased NO_x levels at full load with CE. Improved combustion caused reduction of gas temperature with improved oxygen–fuel ratios might have reduced NO_x levels with semi adiabatic diesel engine. CE with vegetable oil showed lower NO_x emissions at full load in comparison with CE with neat diesel operation. Deteriorated combustion with high viscosity, low volatility and high duration of combustion caused lower heat release rate causing lower NO_x levels with CE with vegetable oil operation. NO_x levels at full load de-

Table 4. Comparative data on particulate emissions and nitrogen oxide level at full load operation

Injection timing (bTDC)	Version of the engine	% of butanol induction	Particulate emissions (Hartridge Smoke Unit)		Nitrogen oxide levels (ppm)	
			Injector opening pressure (bar)		Injector opening pressure (bar)	
			190	270	190	270
27	CE	0% (DF)	48	34	850	950
		0%(CKO)	75	65	750	850
		35%	40	30	500	550
	SADE	0%(CKO)	60	50	1300	1200
		60%	35	20	750	650
29	SADE	0%(CKO)	55	45	1250	1150
	SADE	55%	30	15	400	300
32	CE	0%(CKO)	60	50	950	1050
	CE	35%	35	25	650	750

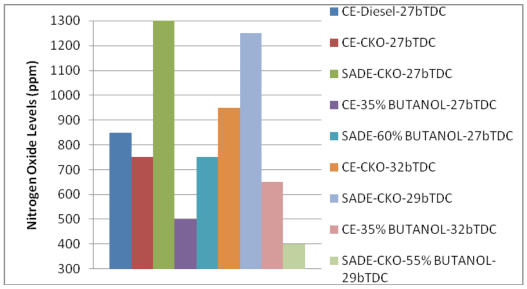


Fig. 6. Histograms showing the variation of nitrogen oxide levels at full load

creased further with carbureted butanol with both versions of the engine. High latent heat of evaporation of butanol absorbed combustion temperatures causing lower NO_x emission with both versions of the engine.

CE with maximum induction of butanol decreased NO_x levels by 33% at recommended injection timing and 32% at optimum injection timing in comparison with CE with neat vegetable oil operation. Semi adiabatic diesel engine with maximum induction of butanol decreased NO_x levels by 50% at recommended injection timing and 68% at optimum injection timing in comparison with semi adiabatic diesel engine with neat vegetable oil operation. Semi adiabatic diesel engine with maximum induction of butanol increased NO_x levels by 18% at recommended injection timing and 35% at optimum injection timing when compared with CE with maximum induction of butanol. High heat release rate in the hot environment provided by low heat rejection combustion chamber might have increased NO_x levels with semi adiabatic diesel engine.

From Table 4, it is observed that CE increased NO_x levels while semi adiabatic diesel engine reduced NO_x emissions with an increase of injector opening pressure. Increase of gas temperatures with CE and decrease of the same might have decreased NO_x emissions with semi adiabatic diesel engine with an increase of injector opening pressure.

These 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. Table 5 shows data of formaldehyde levels and acetaldehyde levels at full load operation with different versions of the engine with maximum induction of butanol varied with an injector opening pressure.

Formaldehyde emissions decreased marginally with advanced injection timing with test fuels. Improved combustion with reduction intermediate compounds might have reduced formaldehyde levels at full load operation. It is noticed that formaldehyde emissions were higher with butanol induction in both versions of the engine. Partial oxidation reaction of butanol with hydro-carbon fuels might have increased formaldehyde levels. The low combustion temperature lead to produce partially oxidized carbonyl (aldehyde) compounds with butanol with vegetable oil operation. With maximum induction of butanol, semi adiabatic diesel engine decreased formaldehyde emissions by 38%, while CE decreased 19% with advanced injection timing. Improved combustion with atomization characteristics of fuel might have reduced formaldehyde levels at

Table 5. Comparative data on formaldehyde levels and acetaldehyde levels at full load

Injection timing (bTDC)	Version of the engine	% of butanol induction	Formaldehyde levels at full load (% Concentration)		Acetaldehyde levels at full load (% Concentration)	
			Injector opening pressure (bar)		Injector opening pressure (bar)	
			190	270	190	270
27	CE	0% (DF)	9.0	8.0	7.0	6.0
		0%(CKO)	12.0	11.0	10.0	9.0
		35%	20.3	19.2	18.3	17.3
	SADE	0%(CKO)	10.0	9.0	8.0	7.0
		60%	23.3	22.2	21.3	20.2
29	SADE	0%(CKO)	8.5	7.4	6.5	5.4
	SADE	55%	14.5	13.3	12.5	11.4
32	CE	0%(CKO)	9.4	8.3	7.5	6.3
	CE	35%	16.4	15.5	14.5	13.4

full load operation.

With maximum induction of butanol, formaldehyde levels were marginally higher with semi adiabatic diesel engine in comparison with CE at recommended injection timing and optimum injection timing. High amount of butanol induction might have increased formaldehyde levels with semi adiabatic diesel engine. Semi adiabatic diesel engine reduced formaldehyde emissions in comparison with CE with neat vegetable oil. Hot environment provided by semi adiabatic diesel engine reduced formaldehyde levels in comparison with CE. Hot environment of semi adiabatic diesel engine completed combustion reactions and reduced the emissions of intermediate compounds, formaldehydes. Hence it is concluded that semi adiabatic diesel engine (SADE) was more suitable for carbureted butanol in comparison with CE. Formaldehyde concentration decreased marginally with an increase of injector opening pressure with both versions of the engine. Improved spray characteristics of fuel might have reduced intermediate compounds leading to reduce formaldehyde levels. Acetaldehyde emissions followed similar trends with formaldehyde emissions.

Conclusion

1. The maximum induction of butanol was 35% with CE, while it was 60% with SADE of mass of the vegetable oil at full load operation at recommended injection timing.
2. Semi adiabatic diesel engine with maximum induction of butanol at recommended injection timing and optimum injection timing reduced particulate emissions, showed comparable nitrogen oxide levels, and increased formaldehyde emissions and acetaldehyde emissions at full load in comparison with CE.
3. Increase of injector opening pressure improved the exhaust emissions with both versions of the engine.

Future scope of the work

A suitable catalytic converter can be designed to control formaldehyde and acetaldehyde emissions from engine run with alcohol with less expensive and easily available catalysts. Sponge iron and manganese ore can be used as catalysts. Air injection into the catalytic chamber can further reduce formaldehyde levels and acetaldehyde levels (Murali Krishna *et al.,* 2012).

Social Significance

Rural employment can be generated by cultivating waste lands. The import of crude petroleum can be saved by adopting alternative fuels like alcohols and vegetable oil and thus gain in the import cost can be used for important sectors like health, poverty, literarily, employment, defense etc,.

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