IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Impact of Fixed Injection Timing on Exhaust Emissions with Ceramic Coated Diesel Engine Using Linseed Oil Based Biodiesel

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Abstract

Research for decreasing the escalating costs of fuel; minimize the exhaust emissions in internal combustion engines and technological innovation studies have been continuing. In this paper, experiments were conducted to determine exhaust emissions in a conventional diesel engine (CE) and ceramic coated low heat rejection (LHR) diesel engine [with ceramic coated cylinder head] with different operating conditions [normal temperature and pre-heated temperature] of linseed oil based biodiesel with fixed injection timing and injector opening pressure. Exhaust emissions [smoke and oxides of nitrogen]. Smoke levels decreased and NOx levels increased with engine with LHR combustion chamber with biodiesel operation. Increase of injector opening pressure and preheated biodiesel reduced exhaust emissions from LHR engine with biodiesel operation. Increased combustion chamber temperature of ceramic coated internal combustion engines causes a decrease in soot and carbon monoxide emissions.

Keywords: Alternate Fuels, Vegetable Oils, Biodiesel, LHR engine, Exhaust emissions, Combustion characteristics.

Introduction

This section deals with need for alternate fuels in diesel engine, problems with use of crude vegetable oil in diesel engine. The advantages in using the preheated vegetable oil in diesel engine, use of biodiesel in diesel engine, effect of increase of injector opening pressure and fixed injection timing on the performance of the diesel engine. The concept of engine with LHR combustion chamber, advantages of LHR combustion chamber, classification of engines with LHR combustion chamber, use of diesel, crude vegetable oil and biodiesel in engine with LHR combustion chamber, research gaps and objectives of the investigations. Another important topic from the view point of internal combustion engines is exhaust emissions. Ceramic coatings applied to diesel engine combustion chambers are aimed to reduce heat which in turn causes shortened ignition delay in ceramic coated diesel engines due to increased temperature after compression because of low heat rejection. Increased combustion chamber temperature of ceramic coated internal combustion engines causes a decrease in soot and carbon monoxide emissions.

Literature Review

The world is presently confronted with the twin crises of fossil fuel depletion and environmental degradation. The fuels of bio origin can provide a feasible solution of this worldwide petroleum crisis (1-2).

It has been found that the vegetable oils are promising substitute, because of their properties are similar to those of diesel fuel and they are renewable and can be easily produced. Rudolph Diesel, the inventor of the diesel engine that bears his name, experimented with fuels ranging from powdered coal to peanut oil. The different fatty acids present [3] in the vegetable oil are palmic, steric, lingoceric, oleic, linoleic and fatty acids. These fatty acids increase smoke emissions and also lead to incomplete combustion due to improper air-fuel mixing. Experiments were conducted [4-7] on preheated vegetable [temperature at which viscosity of the vegetable oils were matched to that of diesel fuel] oils and it was reported that preheated vegetable oils improved the performance marginally and decreased pollution levels of smoke and NOx emissions. The problems of crude vegetable oils can be solved, if these oils are chemically modified to bio-diesel.

Experiments were carried out [8-12] with bio-diesel on direct injection diesel engine and it was reported that performance was compatible with pure diesel operation on conventional engine. However biodiesel operation increased NOx levels.

ISSN: 2277-9655
Impact Factor: 1.852

The other important engine variable to improve the performance of the engine is injection timing. Investigations were carried out [13-16] on single cylinder water cooled vertical diesel engine with brake power 3.68 kW at a speed of 1500 rpm with varied injection timing from 27-34ºbTDC and it was reported that performance of the engine improved with advanced injection timing and increased NOx emissions and decreased smoke levels.

The drawbacks associated with biodiesel for use in diesel engine call for low heat rejection (LHR) diesel engine.

The concept of LHR engine is to reduce heat loss to coolant by providing thermal insulation in the path of heat flow to the coolant. Engines with LHR combustion chamber are classified depending on degree of insulation such as low grade, medium grade and high grade insulated engines. Several methods adopted for achieving low grade LHR combustion chamber are using ceramic coatings on piston, liner and cylinder head, while medium grade LHR engines provide an air gap in the piston and other components with low-thermal conductivity materials like superni, cast iron and mild steel etc. High grade LHR engine is the combination of low grade and medium grade engines.

Engine with LHR combustion chamber with ceramic coating of thickness in the range of 500 microns on the engine components with pure diesel operation [17-19] provided adequate insulation and improved brake specific fuel consumption (BSFC) in the range of 5-7%. The investigations on low grade LHR combustion chamber consisting of ceramic coating on cylinder head were extended [20-22] to crude vegetable oil also and reported that ceramic coated LHR engines marginally improved brake thermal efficiency.

Materials and Methods

This section contains fabrication of engine with LHR combustion chamber, preparation of biodiesel, properties of biodiesel, description of the schematic diagram of experimental set up, specifications of experimental engine, specifications of sound analyzer and gas analyzers, definitions of used values.

The inner side portion of cylinder head was coated with partially stabilized zirconium (PSZ) of thickness of 500 microns in order to convert conventional diesel engine to low heat rejection (LHR) diesel engine.

The chemical conversion of esterification reduced viscosity four fold. Linseed oil contains up to 72.9 % (wt.) free fatty acids [23].The methyl ester was produced by chemically reacting the linseed oil with an alcohol (methyl), in the presence of a catalyst (KOH). A two-stage process was used for the esterification [24-25] of the waste fried vegetable oil. The first stage (acid-catalyzed) of the process is to reduce the free fatty acids (FFA) content in linseed oil by esterification with methanol (99% pure) and acid catalyst (sulfuric acid-98% pure) in one hour time of reaction at 55°C. In the second stage (alkali-catalyzed), the triglyceride portion of the linseed oil reacts with methanol and base catalyst (sodium hydroxide-99% pure), in one hour time of reaction at 65°C, to form methyl ester and glycerol. To remove un-reacted methoxide present in raw methyl ester, it is purified by the process of water washing with air-bubbling. The methyl ester (or biodiesel) produced from linseed oil was known as linseed oil biodiesel (LSOBD). The physic-chemical properties of the biodiesel in comparison to ASTM biodiesel standards are presented in Table-1

Table.1. Properties of Test Fuels

Property	Units	Diesel	Biodiesel	ASTM D 6751-02
Carbon chain	--	C_8-C_{28}	C_{16}-C_{24}	C_{12}-C_{22}
Cetane Number		55	55	48-70
Density	gm/cc	0.84	0.87	0.87-0.89
Bulk modulus @ 20Mpa	Mpa	1475	1850	NA
Kinematic viscosity @ 40ºC	cSt	2.25	4.5	1.9-6.0
Sulfur	%	0.25	0.0	0.05

Oxygen	%	0.3	10	11
Air fuel ratio (stochiometric)	--	14.86	14.2	13.8
Lower calorific value	kJ/kg	42 000	38000	37 518
Flash point (Open cup)	ºC	66	180	130
Molecular weight	--	226	280	292
Preheated temperature	ºC	--	60	--
Colour	--	Light yellow	Yellowish orange	---

The test fuels used in the experimentation were pure diesel and linseed oil based biodiesel. The schematic diagram of the experimental setup with test fuels is shown in Figure 1. The specifications of the experimental engine are shown in Table-2. The combustion chamber consisted of a direct injection type with no special arrangement for swirling motion of air. The engine was connected to an electric dynamometer for measuring its brake power. Burette method was used for finding fuel consumption of the engine. Air-consumption of the engine was measured by an air-box method (Air box was provided with an orifice meter and U-tube water manometer). The naturally aspirated engine was provided with water-cooling system in which inlet temperature of water was maintained at 80ºC 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 [so as to vary the length of plunger in pump barrel] 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 with thermocouples made of iron and iron-constantan.

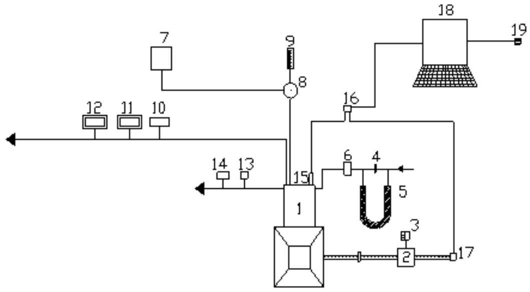
Table.2. Specifications of the Test Engine

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
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	27ºbTDC × 190 bar
Dynamometer	Electrical dynamometer
Number of holes of injector and size	Three × 0.25 mm
Type of combustion chamber	Direct injection type

ISSN: 2277-9655
Impact Factor: 1.852

Fuel injection nozzle	**Make: MICO-BOSCH No- 0431-202-120/HB**
Fuel injection pump	**Make: BOSCH: NO-8085587/1**

Smoke levels and NOx levels were measured with AVL smoke meter and Netel Chromatograph NOx analyzer respectively at full load operation of the engine. The specification of the measuring instruments were shown in Table.3



1.Engine, 2.Electical Dynamometer, 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.

Figure 1. Experimental Set-up

Table 3. Specifications of Analyzers

Name of the analyzer	Measuring Range	Precision	Resolution
AVL Smoke meter	0-100 HSU	1 HSU	1 HSU
Netel Chromatograph NOx analyzer	0-2000 ppm	2 ppm	1 ppm

Different operating conditions of the biodiesel were normal temperature and preheated temperature. Different injector opening pressures attempted in this experimentation were 190 bar, 230 bar and 270 bar.

Results and Dicussion

Results and discussion were to determine the exhaust emissions from the ceramic coated diesel engine .

Exhaust Emissions

This section deals with i) effect of smoke and NOx emissions on human health and its impact on environment, ii) Comparative study of smoke and NOx emissions in CE and engine with LHR combustion chamber with varied injector opening pressure and fixed injection timing with different operating conditions of the vegetable oil.

Smoke and NOx are the emissions from diesel engine cause [26] health hazards like inhaling of these pollutants cause severe headache, tuberculosis, lung cancer, nausea, respiratory problems, skin cancer, hemorrhage, etc. The contaminated air containing carbon dioxide released from automobiles reaches ocean in the form of acid rain, there by polluting water. Hence control of these emissions is an immediate task and important.

This was due to fuel cracking at higher temperature, leading to increase in smoke density. Higher temperature of engine with LHR combustion chamber produced increased rates of both soot formation and burn up. The reduction in volumetric efficiency [27] and air-fuel ratio [27] was responsible factors for increasing smoke levels in the LHR engine near the peak load operation of the engine. As expected, smoke increased in the LHR engine because of higher temperatures and improper utilization of the fuel consequent upon predominant diffusion combustion [28].

When injection timing was advanced to their respective optimum values with both versions of the engine, smoke levels decreased with diesel operation. This was due to increase of air fuel ratios, causing effective combustion in both versions of the engine. The reason for reduction of smoke levels in the LHR engine was reduction of gas temperatures, with the availability of more of oxygen when the injection timing was advanced to its optimum value. This was confirmed by the observation of improved air fuel ratios [27] with the increase of injector opening pressure and with the advancing of the injection timing with both versions of the combustion chamber. However at optimum injection timings, smoke levels were lower in the conventional engine compared to the engine with LHR combustion chamber, due to improved air fuel ratios [27] and volumetric efficiency in the conventional engine.

Smoke levels decreased by 28% and 22% with engine with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. Engine with LHR combustion chamber marginally reduced smoke levels due to efficient combustion and less amount of fuel accumulation on the hot combustion chamber walls of the LHR combustion chamber at different operating conditions of the biodiesel compared to the conventional engine

Conventional engine with pure diesel operation gave lower smoke levels in comparison with biodiesel.

This was due to the higher value of ratio of C/H [$C_{57}H_{98}O_6$], (C= Number of carbon atoms and H= Number of hydrogen atoms in fuel composition (higher the value of this ratio means, number of carbon atoms are higher leading to produce more carbon dioxide and more carbon monoxide and hence higher smoke levels) of fuel composition. The increase of smoke levels was also due to decrease of air-fuel ratios [28] and volumetric efficiency [28] with biodiesel compared with pure diesel operation. Smoke levels were related to the density of the fuel. Since biodiesel has higher density compared to diesel fuel, smoke levels were higher with biodiesel.

Smoke levels decreased [28] at the respective optimum injection timing with test fuels. This was due to initiation of combustion at early period. This was due to increase of air entrainment, at the advanced injection timings, causing lower smoke levels.

Smoke levels were found to be lower with biodiesel operation compared with diesel operation with engine with LHR combustion chamber. The inherent oxygen of biodiesel might have provided some useful interactions between air and fuel, particularly in the fuel-rich region. Certainly, it is evident proof of the oxygen content of biodiesels enhanced the oxidation of hydrocarbon reactions thus reducing smoke levels.

The data from Table 4 shows a decrease in smoke levels with increase of injector opening pressure, with different operating conditions of the biodiesel.

This was due to improvement in the fuel spray characteristics at higher injector opening pressure causing lower smoke levels. Even though viscosity of biodiesel was higher than diesel, high injector opening pressure improves spray characteristics, hence leading to a shorter physical delay period. The improved spray also leads to better mixing of fuel and air resulting in turn in fast combustion. This will enhance the performance [28]

Preheating of the biodiesel reduced smoke levels, when compared with normal temperature of the biodiesel. This was due to i) the reduction of density of the biodiesel, as density was directly related to smoke levels, ii) the reduction of the diffusion combustion proportion with the preheated biodiesel, iii) the reduction of the viscosity of the biodiesel with which the fuel spray does not impinge on the combustion chamber walls of lower temperatures rather than it directed into the combustion chamber**.**

NOx are the precursor pollutants which can combine to form photochemical smog. These irritate the eyes and throat, reduces the ability of blood to carry oxygen to the brain and can cause headaches, and pass deep into the lungs causing respiratory problems for the human beings. Long-term exposure has been linked with leukemia. Therefore, the major challenge for the existing and future diesel engines is meeting the very tough emission targets at affordable cost, while improving fuel economy.

Temperature and availability of oxygen are two favorable conditions to form NOx levels. At peak load, NOx levels increased with test fuels at recommended injection timing due to higher peak pressures, temperatures as larger regions of gas burned at close-to-stoichiometric ratios.

NOx levels increased by 29% and 9% with engine with LHR combustion chamber with biodiesel operation at recommended and optimized injection timings respectively in comparison with conventional engine. Increase of combustion temperatures [28] with the faster combustion and improved heat release rates [28] in the LHR engine cause higher NOx levels in comparison with conventional engine with biodiesel operation.

From the Table.4, it was observed that Increasing the injection advance resulted in higher combustion temperatures and increase of resident time leading to produce more NOx concentration in the exhaust of conventional engine with test fuels.

TABLE.4. DATA OF EXHAUST EMISSIONS AT PEAK LOAD OPERATION

Injection Timing (º bTDC)	Test Fuel	Smoke Levels (Hartridge Smoke Unit)						NOx Levels(ppm)					
		Injector Opening Pressure (Bar)						Injector Opening Pressure (Bar)					
		190		230		270		190		230		270	
		NT	PT	NT	PT	NT	PT	NT	PT	NT	PT	NT	PT
27(CE)	DF	48	--	38	--	34	--	850	----	900	----	950	---
	LSOBD	55	50	50	45	45	40	950	875	1000	925	1050	975
27LHR)	DF	55	--	50	--	45	--	1100	--	1050	--	1000	--
	LSOBD	45	40	40	35	35	30	1225	1175	1175	1125	1125	1075

Biodiesel with both versions of the engine gave higher NOx levels than pure diesel operation. The linseed oil based biodiesel having long carbon chain (C_{20}-C_{32}) [31] recorded more NOx than that of fossil diesel having both medium (C_8-C_{14}) as well as long chain (C_{16}-C_{28}). The increase in NOx emission might be an inherent characteristic of biodiesel due to the presence of 54.9% of mono-unsaturated fatty acids(MUFA) and 18% of poly-unsaturated fatty acids (PUFA). That means, the long chain unsaturated fatty acids (MUFA and FUPA) such as oleic C18:1 and linoliec C18:2 fatty acids are mainly responsible for higher levels of NOx emission [26]. Another reason for higher NOx levels is the oxygen (10%) present in the methyl ester. The presence of oxygen in normal biodiesel leads to improvement in oxidation of the nitrogen available during combustion. This will raise the combustion bulk temperature responsible for thermal NOx formation Many researchers reported that oxygen [33] and nitrogen [35] content of biodiesel can cause an increase in NO*x* emissions. The production of higher NOx with biodiesel fueling is also attributable to an inadvertent advance of fuel injection timing due to higher bulk modulus of compressibility, with the in-line fuel injection system.

From the Table 4, it is noted that these levels increased with increase of injector opening pressure with different operating conditions of biodiesel. NO*x* slightly increased with test fuels as injector opening pressure increased. As seen from the Table.4, that peak brake thermal efficiency increased as injector opening pressure increased. The increase in peak brake thermal efficiency was proportional to increase in injector opening pressure. Normally, improved combustion causes higher peak brake thermal efficiency due to higher combustion chamber pressure [28] and temperature and leads to higher NO*x* formation. This is an evident proof of enhanced spray characteristics, thus improving fuel air mixture preparation and evaporation process.

NOx levels decreased with preheating of the biodiesel as noticed from the Table.4. The fuel spray properties may be altered due to differences in viscosity and surface tension. The spray properties affected may include droplet size, droplet momentum, degree of mixing, penetration, and evaporation. The change in any of these properties may lead to different relative duration of premixed and diffusive combustion regimes. Since the two burning processes (premixed and diffused) have different emission formation characteristics, the change in spray properties due to preheating of the vegetable oil (s) are lead to reduction in NOx formation. As fuel temperature increased, there was an improvement in the ignition quality, which will cause shortening of ignition delay. A short ignition delay period lowers the peak combustion temperature which suppresses NOx formation [26,28]. Lower levels of NOx is also attributed to retarded injection, improved evaporation, and well mixing of preheated biodiesel due to their viscosity at preheated temperatures. Biodiesel has higher value of NOx emissions followed by diesel. This was because of inherent nature of biodiesel as it has oxygen molecule in its composition.

Research Findings and Suggestions

Investigations on study of exhaust emissions and combustion characteristics with engine with ceramic coated LHR combustion were systematically carried out with varied injector opening pressure and injection timing with different operating conditions of the test fuels with various configurations of the combustion chamber. However, engine with LHR combustion chamber increased NOx levels with test fuels and hence study of reduction of NOx emission is necessary.

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ISSN: 2277-9655
Impact Factor: 1.852

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