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TECHNIQUES TO IMPROVE THE PERFORMANCE WHILE REDUCING THE POLLUTANTS LEVEL IN THE EXHAUST GASES OF COMPRESSION IGNITION ENGINES - A REVIEW

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ABSTRACT

This paper describes the various techniques to improve the performance of compression ignition engines while reducing the level of pollutants in the exhaust gases. The pollutants emitted from diesel engine have been recognized as a major air pollution source, which affects the health of living beings and causing ozone layer depletion, green house effect, acid rain and unfavourable ecological environment. In this paper various technical aspects regarding the diesel engine performance improvement, combustion characteristics, methods to control the emission characteristics by modifying technical parameters like fuel injection pressure and timing, compression ratio, thermal barrier coating, fuel modification (blending of nano and chemical additives) and exhaust gas treatment techniques have been discussed in detail.

Keywords: compression ignition engines, engine parameters, fuel modification and exhaust gas treatment techniques.

INTRODUCTION

Compression ignition engines are considered as prime movers in light, medium and heavy duty applications such as automobiles, power plants, marine and industrial sectors due to their reliable operation i.e., lower fuel consumption, and better power performance. The fossil fuels are very limited and may exhaust in coming few decades. In addition, the utilization of fossil fuels is increasing at faster rate due to the population growth and living advancements. However the pollutants emitted from diesel engine affects the health of living beings, ozone layer depletion, green house effect, acid rain, ecological environment and global warming. For better atmospheric environment, improvements are required to reduce the exhaust pollution emitted from the diesel engines. Governments also implement strict emission rules to the engine manufacturers and the customers to follow the emission norms to save the environment from the harmful emissions. Many researchers contributed their efforts to reduce the emissions from diesel engine on par with the performance improvement by engine design modifications, fuel modification and exhaust gas treatment techniques. Fuel modification technique is being used by various researchers to gain specific fuel properties so as to improve performance and reduce the exhaust emissions of diesel engine. Furthermore, the scientific community searches for alternative fuels those are renewable, safe and non-polluting. The renewable fuels such as vegetable oils and alcohols are an alternative to petroleum based fuels and the properties of various fuels given in the Table-1. But the problems like high viscosity and poor volatility of the vegetable oils put obstacle on the end users.

Engine modification

Many researchers have put their valiant efforts to improve the performance while reducing the level of pollutants in the exhaust gases of compression ignition engines mainly by modifying the engine hardwares, fuel modification and exhaust gas recirculation and treatment. The performance and the level of pollutants in the exhaust gases are affected by many technical parameters.

Effect of injection pressure on the working characteristics

The fuel injection pressure is one of the significant operating parameters which have an effect on atomization of fuel and mixture formation. Gumus *et al*. [1] carried out experiments to evaluate the performance and emissions on a single cylinder, naturally aspirated, air cooled, direct injection (DI) diesel engine with biodiesel-diesel fuel blends by varying the fuel injection pressure (18, 20, 22 and 24 MPa) at different loads and revealed that Brake Specific Fuel Consumption (BSFC), and Exhaust Gas Temperature (EGT) were increased for the blends with higher percentage of biodiesel due to low heating value and more oxygen content of biodiesel compared to those of neat diesel. However the level of pollutants in the exhaust gases (HC, CO and smoke) were decreased with the increase in biodiesel percentage due to complete combustion of biodiesel as a result of the presence of more oxygen molecules. In addition they have shown that the increased injection pressure helps as decreased BSFC for higher biodiesel-diesel blends and reduced level of pollutants (HC, CO and smoke) because of the improved combustion whereas NO_x emission was increased as a result of high combustion temperature in the cylinder. Similar experimental study was presented by Sukumar *et al*. [2] by varying the fuel injection pressure (200, 220 and 240 bar) on a DI diesel engine (4.4 kW at 1500 rpm) with high Linolenic Linseed Oil Methyl Ester (LOME). They have reported that BSFC was high for LOME compared to that of diesel at all loads and injection pressures due to high density and low heating value of LOME. Based on the results, they have concluded that the fuel injection pressure of 240 bar was the optimum for the LOME.

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Table-1. Fuel properties.

Investigators	Description	Density @ 15°C, (kg/m^3)	Kinematic viscosity @ 40°C, cSt	Flash point, °C	Net calorific value, MJ/kg	Cetane number
Celikten *et al*. [3]	Diesel fuel	815	4.3 @ 27°C	58	43.35	47
	Rapeseed oil	872	11 @ 27°C	275	39.76	37.6
	Soybean oil	914	39 @ 27°C	69	37.62	37
Musthafa *et al*. [4]	Rice bran oil	927	38.8	270	37.9	-
	Pongamia oil	934	38.2	220	35.6	-
	Rice bran methyl ester (RME)	877	5.6	153	39.6	-
	Pongamia methyl ester (PME)	886	5.3	147	36.05	-
Rahiman *et al*. [5]	Pongamia oil	886	-	147	36.05	54
	Ethanol	750	-	16.6	25.5	8
	Diethyl ether	714	-	28	31.87	>125
Ravikumar *et al*. [6]	Mahua biodiesel	880	6.04	170	41.81	52.4
Selvan *et al.* [7]	Ethanol	790	1.13	13.5	25.18	6
	Castor oil	965	24.5	230	39.5	48
	D70C10E20	827	2.35	11	39	44.6
Kannan *et al*. [8]	Waste cooking palm oil based biodiesel	866	4.56	170	38.03	66
Sadhik Basha and Anand [9]	Jatropha biodiesel	895	5.25	85	38.88	53
Sivalakshmi and Balusamy [10]	Neem oil methyl ester	867	4.5	165	41	51
Raheman and Ghadge [11]	mahua biodiesel	880	3.98	208	36.8	-

At this condition, the thermal efficiency was similar to diesel whereas HC, CO and smoke emissions were less than those of neat diesel. They also reported that at full load the ignition delay was low and peak pressure was high at higher injection pressures compared to diesel. The period of combustion was nearly same at all the injection pressures. Celikten *et al*. [3] examined the performance and emissions of a four cylinder direct injection diesel engine by using diesel fuel, rapeseed oil and soybean oil methyl ester with three different fuel injection pressures (250, 300 and 350 bar) and reported that the performance and emission values of rapeseed oil and soybean oil methyl esters were found to be nearly the same as those of diesel fuel when injection pressure was increased to 300 bar. They also reported that for rapeseed biodiesel emissions, reduction in smoke by 122% with increasing the injection pressure from 250 to 350 bar and reduction in CO emission by 21%, NO_x emission increased by 21% with the higher injection pressure. They further reported that for soybean biodiesel emissions, reduction in smoke by 16.7 %, reduction in CO by 28% and NO_x emission was increased by 20% with the injection pressures varying from 250 to 350 bar. Comparison of three different fuels showed that, rapeseed and soybean biodiesels have less CO and smoke level than diesel fuel but have high NO_x emission for all injection pressures. Yogish *et al*. [12] carried out experiments to compare the performance and emissions on a single cylinder water cooled, direct injection, CI engine (3.75 kW at 1500 rpm) fueled with composite biodiesel blends (blends of Jatropha and Pongamia biodiesel) by varying the fuel injection pressures (160 and 180 bar). Methyl esters of Jatropha and Pongamia, blends of methyl esters of composite biodiesel and the neat diesel are prepared and tested. They found that the BSFC was decreased with the increasing load for all the tested fuels and BSFC was increased with increase in amount of biodiesel in the blends. They also found that that the fuel consumption was 20% lower and Brake Thermal Efficiency (BTE) was 34% higher for composite biodiesel blend than the values of neat diesel. In addition they found that the improvement in the performanceand the level of pollutants (HC, CO and NO_x) in the exhaust gasses was decreased significantly for composite biodiesel.

Jindal *et al*. [13] conducted experiments to evaluate combined effects of injection pressure (150, 200 and 250 bar) and compression ratio (16, 17 and 18) on the performance and emissions on a single cylinder, water cooled, Variable Compression Ratio (VCR) 3.5 kW diesel engine by employing the Jatropha methyl ester. They

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reported that BSFC was decreased with the increase in the compression ratio and among the three compression ratios the lowest BSFC found at compression ratio of 18. In addition they set the standard operating conditions in terms of injection pressure as 210 bar and compression ration as 17.5 and concluded that the optimum working conditions were obtained for the injection pressure of 250 bar and the compression ratio of 18; BSFC and BTE were improved by 10% and 8.9%, respectively for the biodiesel. Related to emissions, increase in compression ratio leads to increase in emission of HC and EGT whereas smoke and CO emission was reduced. NO_x emission was found as unaffected at all the tested injection pressures. The higher injection pressure helps in keeping the emissions of HC, NO_x and smoke at a lower level. For all combinations of compression ratio and injection pressure, the emissions of HC, NO_x, smoke and EGT were low with pure bio-diesel against those of neat diesel.

Effect of injection timing on the working characteristics

In line with the investigations to find the effects of fuel injection pressure, many scientists have conducted the investigations to establish the effects of fuel injection timing. The fuel injection timing causes the variation of delay period, rate of evaporation of fuel, rate of combustion, etc. and subsequently it affects the engine performance, combustion and emission characteristics. Sayin *et al*. [14] evaluated the exhaust emissions of a single cylinder, four stroke, direct injection, naturally aspirated diesel engine that was fueled with ethanol blended diesel fuel at various injection timings (21°, 24°, 27°, 30° and 33° Crank Angle Before Top Dead Center (CA BTDC)), speeds (1000, 1200, 1400, 1600 and 1800 rpm) and loads (15 and 30 Nm). They have reported that NO_x emission was increased and HC and CO emissions were decreased with the increase in the proportion of ethanol in the fuel mixture because of high peak temperature in the cylinder for the injection timing of 27° CA BTDC. Whereas NO_x emission was decreased and HC and CO emissions were increased for all test conditions at the retarded injection timings (21° and 24° CA BTDC). Conversely, HC and CO emissions were decreased and NO_x emissions were increased for all test conditions with the advanced injection timings (30° and 33° CA BTDC). Similar study was conducted by Sayin *et al*. [15] to evaluate the performance and emissions on a diesel engine using diesel-methanol blends (0, 5, 10 and 15%) by varying the fuel injection timing (15°, 20° and 25° CA BTDC) at four different loads (5, 10, 15, 20 Nm). They have found that BSFC was increased with the methanol percentage in the blend compared to that of neat diesel fuel due low calorific value of methanol. But the level of pollutants such as HC, CO and smoke emissions were decreased and NO_x emission was increased with increase in the amount of methanol in the fuel blend against that of neat diesel for the injection timing of 20° CA BTDC. Similar trend was observed of the advanced injection timing (25° CA BTDC) whereas the trend was reversed for retarded injection timing (15° CA BTDC).

Ganapathy *et al*. [16] carried out an experimental investigation to compare the performance and emissions on a single-cylinder, air cooled, Greaves Cotton model GL 400 II A, diesel engine with Jatropha biodiesel with diesel by varying the fuel injection timing (20°, 15° and 10° CA BTDC), load (5, 10, 15 Nm), and engine speed (1800, 2500, 3200 rpm). They found that the optimum injection timing to be 20° CA BTDC for Jatropha biodiesel as the fuel for the CI engine with minimum BSFC, CO, HC and smoke emission and with maximum BTE, peak pressure, Heat Release Rate (HRR) and NO emission. They also observed that HC and CO emissions were increased with the increase in engine speed due to inefficient combustion and the smoke was increased with the engine speed upto 2500 rpm and further increase of the engine speed the smoke intensity was decreased for the increase in engine speed for the diesel and Jatropha biodiesel. Kannan and Anand [17] analyzed the impact of engine injection strategy such as injection pressure (220 to 300 bar) and injection timing (23°, 25.5° and 28° CA BTDC) on a single cylinder, DI naturally aspirated diesel engine under different loads at a constant speed by using neat diesel, neat waste cooking palm oil methyl ester (biodiesel) and a fuel blend (60% of neat diesel + 30% of waste cooking palm oil methyl ester + 10% ethanol). Based on the results they have reported that BTE was increased with the increase in load for the fuel blend at all injection pressures and timings and they attained the maximum BTE of 31.3 % for the fuel blend, which was 2.6% more than that of biodiesel and 3.5% more than that of diesel. The lowest BSFC was obtained as 0.29 kg/kW-hr for the fuel blend which was 10.6% more than that of neat biodiesel and nearly same to that of diesel at an injection pressure of 240 bar and injection timing of 25.5° CA BTDC at full load. They compared the results of fuel blend with diesel and showed that reduction in CO, smoke emission and NO by 33, 27.3 and 4.3%, respectively while HC increased slightly. Agarwal *et al*. [18] carried out a similar experimental investigation to evaluate the performance, emissions and combustion characteristics on a single cylinder research engine (AVL, 5402) at different Injection Pressures (IP) and injection timings. The experiments were conducted at a constant speed (2500 rpm) with two injection pressures (500 and 1000 bar) and different injection timings (15°, 12.75°, 9.375°, 7.125° and 4.875° CA BTDC). They reported that the cylinder gas pressure and HRR were found to be higher at lower IP (500 bar), while at higher IP (1000 bar) knocking was observed. With the advanced injection timings gave higher HRR in early combustion stages. They also reported that the BTE, EGT and brake mean effective pressure (BMEP) were increased with the increase in injection pressure, however exhaust emissions HC was decreased and NO_x was increased. For advanced injection timing, BMEP and BTE were increased while BSFC and EGT were reduced. Lower HC emissions and higher NO_x emissions were observed with advanced injection timings. Saravanan *et al*.

[19] conducted experiments to evaluate the NO_x emissions on a single cylinder, naturally aspirated, air cooled, DI diesel engine by varying the three important factors; fuel injection timing (20.9°, 23.4° and 25.9° CA BTDC), quantity of exhaust gases recycled (0, 10 and 15%) and fuel injection pressure (210, 230 and 250 bar) by using crude rice bran oil methyl ester. They found that optimum combination of factor levels on the variables were obtained by using Design of Experiments (DOE) and Taguchi's L9 orthogonal array and observed a reduction in NO_x emission with a marginal increase in smoke. For the reduction in NO_x emission, EGR is a major influencing factor at no-load and part-load with less influence on smoke density while fuel injection timing is more influential at full load.

Effect of compression ratio on the working characteristics

Compression ratio is an important factor and it determines the state of air - fuel mixture at the end of compression, which affects the combustion phenomenon. Sayin and Gumus [20] carried out experiments at different compression ratios (CRs), injection timings (ITs) and injection pressures (IPs) on the performance and emissions of a DI diesel engine by using biodiesel (5, 20, 50 and 100 %) blended with diesel fuel for three different CRs (17, 18 and 19), ITs (15°, 20° and 25° CA BTDC) and IPs (180, 200 and 220 bar) at 20 Nm engine load and 2200 rpm. They have reported that BSFC was increased with the increase of biodiesel percentage in the fuel blend due to low heating value of biodiesel. Subsequently they observed that by increasing the injection pressure, BSFC could be decreased due to improved atomization and better mixing process. In addition, they mentioned that increased in the compression ratio cause a higher BTE due to better combustion and higher lubricity of biodiesel. The exhaust emissions such as HC, CO and smoke were decreased while NO_x emission was increased with the increase in compression ratio. HC, CO, and smoke emissions were decreased and NO_x was increased with the increase in the injection pressures for the all fuel blends and the retardation of the injection timing caused the decreased NO_x emission due to lower combustion temperature in the cylinder. They reported that good results for BSFC and BTE were obtained at the highest CR and IP for the original IT of 30° CA BTDC. The HC, CO and smoke emissions were decreased while NO_x emission was increased with an increase in IP, IT and CR. Selvan *et al.* [21] compared the combustion characteristics of a single-cylinder four stroke DI Variable Compression Ratio (VCR) engine at the compression ratios (15, l7 and 19) by using neat diesel and biodiesel (Jatropha methyl ester), and ethanol blends as a fuel. They found that the cylinder gas pressure, maximum rate of pressure rise and heat release rate were increased with higher ethanol concentration owing to longer ignition delay. They also found that ignition delay was decreased with the compression ratio. Muralidharan and Vasudevan [22] investigated on the performance and emissions of a VCR multifuel engine for the compression ratio of 18, 19, 20, 21 and 22 by using waste cooking oil methyl ester and its blends (20, 40, 60 and 80% by volume) with the diesel at a constant speed of 1500 rpm. Based on the results they have reported that combustion pressure was higher at higher compression ratio for the waste cooking oil blends. They also reported that maximum BTE of 31.48% was obtained for waste cooking oil methyl ester blend (B40) and 26.08% for diesel and BSFC observed was 0.259 kg/kW-hr for the blend of B40 and 0.314 kg/kW-hr for diesel at a compression ratio of 21 at 50% load. BTE was increased with the increase in compression ratio of the engine for all the tested fuels. They further reported that HC emission was increased with the compression ratio for the blend B40 and HC emission was decreased for the other blends such as B20, B60 and B80 at higher compression ratio. Nagaraja *et al.* [23] investigated the performance and emissions of CI engine at 1500 rpm by varying the compression ratio (17, 18 and 19) of corn oil methyl ester (COME) and palm oil methyl ester (POME). They observed that combustion pressure was increased for the biodiesel with the compression ratio against that of neat diesel. They also observed that shorter ignition delay and lower heat release rate at higher compression ratio for POME when compared to neat diesel. The BTE was found to be maximum for POME (40.97% at CR 19:1) for all compression ratios at full load. The BSFC was reduced with the increase in compression ratio for all the tested fuels and the exhaust emissions such as HC and CO were increased with the increase in compression ratio. Kassaby *et al.* [24] evaluated the performance and emissions of TD43F VCR diesel engine by varying compression ratio (14, 16 and 18) and varying the speeds from 1000 to 2000 rpm, (in the steps of 250 rpm) by using waste cooking oil-diesel blends (B10, B20, B30 and B50) and reported that the BSFC was decreased and engine torque was increased with the increase in compression ratio for all the blends. As an effect of deceased BSFC, the BTE had a positive response for the increase in the compression ratio. They also reported that reduction in HC emission by 52%, CO emission by 37.5% and NO_x emission was increased by 36.84% as the CR changed from 14 to 18. The delay period was decreased by 13.95% as CR changed from 14 to 18. Bayraktar [25] investigated the performance and emissions of a water cooled CI engine by varying the compression ratio (19, 21, 23 and 25) and engine speed (1000 to 1600 rpm, in the steps of 200 rpm) by using diesel-methanol (2.5 to 15% increments of 2.5%) - dodecanol (1%) blends. He stated that the BSFC was decreased and the engine efficiency was increased with the percentage of methanol (upto 10%) with the blend of diesel- methanol (DM10).

Effect of multiple injections on the working characteristics

Park *et al.* [26] studied the effect of multiple injection strategies on combustion and exhaust emissions characteristics of a C.I. engine by using biodiesel. They analyzed and found that the multiple-injection modes have higher Indicated Mean Effective Pressure (IMEP) than the corresponding value of single-injection mode and the pilot injection method showed higher IMEP than the split injection mode. The multiple-injection modes showed that the short injection interval induced a decrease of soot, HC and CO emissions, while NO_x emission was increased. They have concluded that the reduced size of the injected fuel particles in the case of the multiple-injection modes causes the improvement in the performance and emission characteristics. Similar study was carried out by Suh [27] by employing the multiple injections and he founda that the exhaust emissions such as HC, NO_x and soot emissions were decreased and CO formation was increased at lower compression ratio.

Effect of thermal barrier coating on the working characteristics

In diesel engines, about 20 percent of fuel energy is rejected to coolant fluid. Thermal barrier coatings (TBC) are providing thermal insulation for the heat engine components reduce the in-cylinder heat transfer from the engine combustion chamber as well as reducing component structural temperatures and cause a better working characteristic. The materials like Al_2O_3, ZrO_2, $CaZrO_3$-NiCrAl, Al-20%SiC are being used TBC. Comparison of experimental results of Thermal barrier coated (TBC) engine with those of original engines given in the Table-2. Musthafa *et al*. [4] conducted experiments to evaluate the performance and emission characteristics of a Kirloskar TV-I, single cylinder, water cooled, DI diesel engine by using a nanoceramic Al_2O_3 as a coating material on the combustion chamber surfaces (cylinder head, cylinder liner, valves and piston crown faces) and fuels like Rice bran Methyl Ester (RME), Pongamia methyl ester (PME), and blends of RME and PME. They found that increased engine power, reduction in BSFC and improvements in exhaust gas emissions (except NO_x) and smoke in the ceramic coated engines against that of the uncoated engine. The results of their works given in the Table-3. Aydin [28] presented his studies to establish the effects of zirconium oxide (ZrO_2) as TBC on the performance and emission characteristics of a diesel engine by fueling cottonseed oil and sunflower oil and found that thermal efficiency, power and torque values were improved for the vegetable oil blends due to TBC. They also found that sunflower oil blends have better torque and power values compared with cotton seed oil blends due to that sunflower oil having higher heating value. But the level of pollutants in the exhaust gases, HC and CO was decreased for the vegetable oil blends due to the excess oxygen available. On the other hand, NO_x emission was increased due to the increased combustion temperature in the coated engine. Smoke emission was decreased for the vegetable oil blends in coated engine compared to the diesel fuel in both coated and uncoated engine. They also found that HC, CO and smoke emissions were decreased while NO_x emission was increased with the increase in engine speed for the all tested fuels.

Buyukkaya *et al*. [29] conducted experiments to evaluate the performance and emissions on a six cylinder, Turbocharged Direct Injection (TDI) diesel engine by using thermal barrier coatings at different speeds (1000 to 2400 rpm, in steps of 200 rpm) and injection timings (18° and 16° CA BTDC). The cylinder head and valves were coated with $CaZrO_3$ material and piston was coated by $MgZrO_3$ with a thickness of 350 µm and over a 150 µm thickness of NiCrAl bond coat. They have reported that BSFC was decreased by 6% and the NO_x emission was increased by 9% in the coated engine against that of the uncoated engine due to the higher exhaust gas temperatures in the coated engine. They have also reported that the fuel injection timing of the standard engine was assumed to be 20° CA BTDC, NO_x emission was achieved below those of the standard engine by 11% and 26% at 18° and 16° CA BTDC respectively. Similar experimental setup was presented by Buyukkaya and Cerit [30]. They studied the effects of injection timing on nitrogen oxide (NO_x) emissions in a low heat rejection (LHR) TDI diesel engine. They observed that BSFC was decreased for LHR engine against that of original engine with the engine speeds at low, medium and full loads due to higher surface temperatures of combustion chamber. NO_x emission was decreased in the range of 35-53% when retarding the injection timing from 20º to 16º CA BTDC for the LHR engine. Uzun *et al*. [31] investigated the effects of thermal barrier ceramic coatings on the performance and exhaust emissions of a diesel engine. The cylinder head and valves were coated with 0.35 mm thickness of $CaZrO_3$ over a 0.15 mm thick NiCrAl bond coat and the piston was coated with $MgZrO_3$. They observed that the BTE was increased by 10% and the BSFC was decreased by 2% with the coated engine against that of uncoated engine. The pollutants in the exhaust gases such as HC, CO and particulate emissions were decreased by 40, 40 and 48 % respectively in the coated engine. On the other hand NO_x emission was increased with the increase of temperature in the coated engine. Similar study was presented by Rahiman *et al*. [32] analyzed the effects on the performance and emission parameters by using DB (Diesel 50% + Pongamia

Table-2. Comparison of experimental results of thermal barrier coated (TBC) engine with those of original engines.

Investigators	Coating Material	Performance of TBC engines with compared to standard engines
Musthafa *et al*. [4]	Aluminum oxide (Al_2O_3)	BTE increases, bsfc decreases; HC, CO and smoke decreases; NOx and EGT increases
Aydin [28]	ZrO_2	Power increases, bsfc decreases; HC, CO smoke decreases; NO_x increases;
Buyukkaya *et al*. [29]	$MgZrO_3$ over a NiCrAl bond coat, and $CaZrO_3$	bsfc decreases, NO_x decreases; (TBC and injection timing)
Uzun *et al*. [31]	$CaZrO_3$ over NiCrAl bond coat and $MgZrO_3$	BTE increases, bsfc decreases; HC,CO and smoke decreases; NO_x and EGT increases
Rahiman *et al*. [5]	Al_2O_3 and yttria-stabilized zirconia	BTE increases, CO decreases; NO_x increases
Ravikumar *et al*. [6]	Al-20% SiC	BTE increases,; HC and smoke decreases; NO_x and EGT increases

Table-3. Improved performance and emission values of the test fuels used in the Al_2O_3 coated engine, compared with the uncoated engine diesel operation at 100% power output. (Musthafa *et al*. [4].

	Test fuels in Al_2O_3 coated engine				
Description	**Diesel**	**RME20 with diesel**	**PME20 with diesel**	**RME100**	**PME 100**
Brake thermal Efficiency	8.9%, increases	11.25%, increases	9.9%, increases	7.9%, increases	6.7%, increases
Specific fuel consumption	3.8%, decreases	8.4%, decreases	5.4%, decreases	0.7%, increases	2.7%, decreases
Hydrocarbon Emission	41.9%, decreases	44.2%, decreases	51.2%, decreases	62.8%, decreases	55.8%, decreases
NO_x	21.9%, increases	8.2%, increases	13.2%, increases	18.5%, increases	16.5%, increases
Smoke	19.6%, decreases	21.2%, decreases	20.2%, decreases	25.8%, decreases	28.5%, decreases
Exhaust gas Temperature	8.7%, increases	5.9%, increases	7.5%, increases	3.2%, increases	4.4%, increases

biodiesel 50% blend), DBE (Diesel 50% +Pongamia biodiesel 40% + Ethanol 10%), DBD (Diesel 50% + Pongamia biodiesel 40% + Diethyl ether 10%) fuels with uncoated diesel engine and TDBE (Diesel 50% + Pongamia biodiesel 40% + Ethanol 10%), TDBD (Diesel 50% + Pongamia biodiesel 40% + Diethyl ether 10%) with thermal barrier coated diesel engines. The diesel engine parts such as Piston crown, cylinder head, and valve faces were coated with TBC with the layers of aluminum oxide Al_2O_3 of 0.3 mm and yttria-stabilized zirconia of 0.2mm. They have found that BTE was increased with the TBC engine as the coating reduces the heat loss to the surroundings and the BTE was increased in the order as DBE, DB, TDBE, DBD, and TDBD fuels. They have also found that NO_x emission was increased with the load and it was increased for the TDBD and TDBE fuels due to increase in the combustion temperature. Ravikumar *et al*. [6] conducted experiments to evaluate the performance and emission characteristics on Kirloskar TV 1, water cooled, DI diesel engine (IP = 220 bar and IT = 23° CA BTDC) by using Madhuca indica biodiesel. The combustion surfaces of the engine were coated with Al-20 % SiC material. They have reported that the percentage reduction in BSFC as 2.23, 2.21, 1.99, 1.32 and 1.28% for the coated engine with the blends of B0, B25, B50, B75 and B100 respectively against that of uncoated engine at full load. BTE was increased by 1.68, 1.65, 1.29, 1.37 and 1.14% for the blends B0, B25, B50, B75 and B100 respectively in the coated engine against that of uncoated diesel engine at full load. They have also reported that NO_x emission was maximum for the neat biodiesel in the coated engine against that of uncoated engine due to higher EGT in the combustion chamber at full load.

Fuel modification

A large number of fuel additives have been considered by researchers for enhancing the performance and also reducing emissions from diesel engines. The effect of some of fuel additives such as nano, metal based additives, emulsions, oxygenates and antioxidants are considered in this paper.

Effect of Nano additives on the working characteristics

Nano materials are considered as a fuel borne catalysts to improve fuel properties due to their enhanced surface area / volume ratio, rapid evaporation and shorter ignition delay characteristics. Due to their surface area / volume ratio characteristics of nano particles the degree of mixing and chemical reactions are improved during the combustion leading to better performance and emission characteristics of the diesel engine. Addition of nano particles such as Alumina, aluminium, ceria, carbon nanotube to any conventional fuels enhances the combustion efficiency, ignition and favours shorter ignition delay. Sadhik Basha and Anand [32] conducted experiments to evaluate the effects of carbon nanotubes (CNT) blended with diesel and observed a considerable improvement in the BTE and reduced harmful pollutants compared to that of neat diesel due to the combustion enhancing property of nano particles. The experimental setup used by Sadhik Basha and Anand was shown in Figure-1. The same team [33] have reviewed the applications of nanoparticle/nanofluids in diesel engines and stated that adding a suitable quantity of nanoparticles/carbon nanotubes to conventional fuels to reduce the evaporation time and in turn favours the shorten ignition delay. The same team [34] evaluated the effects of alumina nanoparticles (25 and 50 ppm) blended jatropha biodiesel fuel and the performance and emission characteristics were shown in Figure-2 and Figure-3 and further and reported that the peak pressure and heat release rate was lower for the alumina nanoparticles blended biodiesel fuels compared with the jatropha biodiesel due to the greater surface area to volume ratio and improved ignition properties of alumina nanoparticles which initiate the early combustion. The cylinder gas pressure for the jatropha biodiesel fuel (JBD) was observed as 72.3 bar compared to 71.1 and 69.3 bar for JBD25A and JBD50A respectively. They also reported that maximum BTE was observed as 28.1, 26.1 and 24.8% and lower the BSFC was observed as 0.32, 0.34, and 0.37 kg/kW.hr for the JBD50A, JBD25A and JBD fuel, respectively at the full load. But the level of pollutants in the exhaust gases, the NO_x emission was observed as 1015, 1060 and 1282 ppm and smoke was observed as 58, 60, and 67% for the JBD50A, JBD25A and JBD fuel respectively at the full load.

Selvan *et al.* [7] determined the influence of cerium oxide (25 ppm) nanoparticles as additive in neat diesel and a fuel blend (70% of neat diesel + 10% of Castor oil (biodiesel) + 20% of ethanol (D70C10E20)) on the performance and emission characteristics of a single cylinder, computerized VCR engine. They have reported that BSFC was better for the diesel ethanol blends than neat diesel at all the bmep due to the lower calorific value of the diesel ethanol blend and lowest BSFC was found as 0.3586 kg/kW-hr for the D+CERIA25 blend and 0.3931 kg/ kW-hr for neat diesel at the bmep of 0.44 MPa due to addition of cerium oxide which promotes combustion. But the level of pollutants in the exhaust gases such as HC, CO and smoke were decreased with the addition of cerium oxide against that of neat diesel due to cerium oxide acting as oxygen buffer. But NO_x emission was lower for neat diesel compared to all the fuel blends. Similar study was presented by Sajith *et al.* [35] conducted experiments using cerium oxide (20-80ppm) nanoparticles as additive in Jatropha biodiesel in a single cylinder, water-cooled compression ignition engine at a operating speed of 1500 rpm. They have reported that the BSFC was decreased and BTE was increased with the addition of cerium oxide nanoparticles. They also reported that emission levels of HC and NO_x were appreciably decreased with the addition of cerium oxide nanoparticles. They have concluded that dosing of ceria nanoparticles to the base fuel would act as an oxygen buffer and acting as an effective catalyst due to its higher surface area - to volume ratio of nanoparticles ensuing improvement in the fuel efficiency and reduction in emissions.

Effect of metal based additives on the working characteristics

In some research studies attempts was made on fuel modification techniques, metallic additives (catalytic additives) were added to the diesel fuel to gain better performance and emission characteristics in a diesel engine. The thought of adding a metallic additive to the diesel fuel was to enhance the combustion characteristics of the diesel fuel by a concept called catalytic combustion. Some of the metal additives (such as $FeCl_3$, Fe, Ferrous picrate, Ni, Mn and Mg) used as fuel borne catalysts for biodiesels to improve the combustion and reduce the exhaust emissions.

Guru *et al.* [36] investigated the effect of magnesium (12 μmol Mg) additive on Cussons P8160 type DI diesel engine to evaluate the performance and emissions by using chicken fat biodiesel. The engine was tested by using blend of 10% chicken fat biodiesel and diesel fuel (B10) at the engine speeds of (1800 to 3000 rpm, in steps of 200 rpm). They have found that the BSFC of biodiesel fuel was increased by 5.2% due to the lower heating value of biodiesel and BTE of biodiesel fuel was decreased by 4.8% at all the engine speeds against that of neat diesel fuel. They also found that CO and smoke emissions were decreased by 13 and

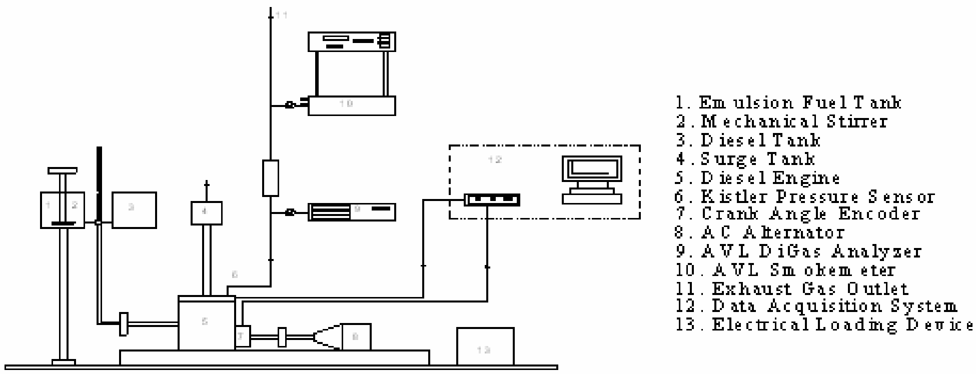

Figure-1. Schematic layout of the experimental setup [9, 32, 34].

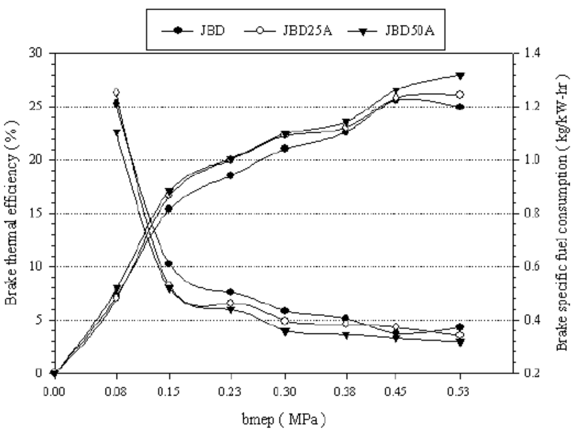

Figure-2. Variation of brake thermal efficiency and brake specific fuel consumption with bmep (Sadhik Basha and Anand [29]).

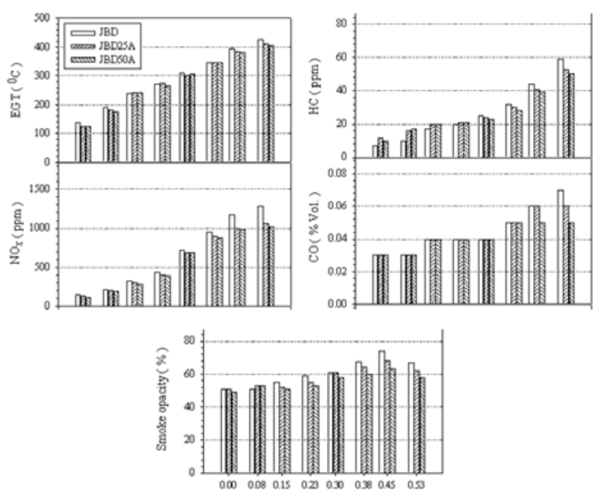

Figure-3. Variation of EGT, NO_x, HC, CO and smoke opacity with bmep (Sadhik Basha and Anand [29]).

9% respectively, but NO_x emission was increased by 5% against those of neat diesel fuel. Kannan *et al*. [33] discussed the effect of ferric chloride ($FeCl_3$) as Fuel Borne Catalyst (FBC, 20 µmol / L) on a single cylinder, water cooled, naturally aspirated, DI diesel engine by using waste cooking palm oil biodiesel. They conducted experiments for the injector pressure and timing 220 bar and 23° CA BTDC and 280 bar and 25.5° CA BTDC. They reported that BSFC was decreased by 18.4% and BTE was increased by 1.8% for the FBC added biodiesel against that of the biodiesel without FBC for the hardware settings of 280 bar and 25.5° CA BTDC. In addition, for the same settings HC, CO and smoke emissions were decreased by 26.6, 52.6 and 6.9%, respectively for the FBC added biodiesel against that of without FBC biodiesel. Zhu *et al*. [37] examined the influence of Fe (ferrous picrate) homogeneous combustion catalyst on the performance of single cylinder, air cooled, DI diesel engine at a operating speeds of 2800, 3200 and 3600 rpm with the different dosing ratio of (1: 5000, 1:10, 000) Fe. They found that the BSFC was decreased and the BTE was increased with the addition of the catalyst. In addition, the higher peak cylinder pressure, shortened ignition delay and faster heat release rate were found for the catalyst added diesel. Similar experimental study was presented by Yu Ma *et al*. [38]. They analyzed the effects of homogeneous combustion catalyst Fe (ferrous picrate) on the performance and emissions of a YANMAR L48AE diesel engine (AET Ltd.). The engine was tested at four different loads of 0.14, 0.21, 0.33 and 0.42 MPa, two speeds of 2800 and 3200 rpm and the two dosing ratios of 1:3200 for FTC (FTC is a catalyst which modifies the chemistry of the fuel combustion process, accelerates the fuel burning and oxidizes the engine carbon deposits, existing combustion chamber and exhaust system) and 1:10000 (by volume) for FPC (Fuel Performance Catalyst) combustion catalysts made from ferrous picrate. They found that BSFC was decreased for the FTC/FPC catalyst added fuels against that of neat diesel under all engine test conditions and the maximum fuel saving of 3.7% for the FTC-3200, whereas 3.1% for the FPC-10000. But the level of pollutants in the exhaust gases; HC, CO and smoke were decreased by 13, 21 and 39%, respectively whereas NO_x emission was increased by 6% for the catalyst added diesel against that of neat diesel fuel.

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Keskin *et al*. [39] investigated the influences of crude tall oil biodiesel that produced from paper plant with nickel and manganese based fuel additive on the performance and emission characteristics of DI diesel engine. They synthesized nickel (Ni) and manganese (Mn) based fuel additives by reacting tall oil resinic acid reacted with nickel oxide (NiO) and manganese dioxide (MnO_2). The metal based additives were added a fuel blend of 60% tall oil biodiesel and 40% diesel at the rate of 8 and 12 μmol/l. They have reported that BSFC was increased for the biodiesel fuel due to lower calorific value of biodiesel fuel and BSFC was increased from 3.22 - 6.00% for the biodiesel fuels against that of neat diesel fuel. They also reported that CO emission was decreased for the Mn and Ni added biodiesel fuel against that of neat diesel fuel due to additives and CO emission was decreased for the Mn added biodiesel fuel compared to Ni added biodiesel fuel. NO_x emission was decreased for the Ni added biodiesel fuels.

Effect of emulsions on the working characteristics

Simultaneously, researchers spend their valuable efforts on fuel modification techniques by adding some chemical reagents and water with the conventional diesel fuel without a negative impact on the fuel consumption and the engine design. Saravanan *et al*. [40] studied the performance and emission characteristics of diesel water emulsions in a single cylinder 8 HP diesel engine and reported that BSFC was increased and no significant change in the BTE for water blended diesel against that of neat diesel. They also reported that the emissions HC and CO were decreased with the increase in load for water blended diesel compared to neat diesel. NO_x emission was decreased through inclusion of water by lowering the peak combustion temperatures through high heat of vaporization. Sadhik Basha and Anand [9] carried out experimental investigation on CI engine that was fueled with alumina nanoadditives (25, 50 and 100 ppm) blended diesel-water emulsion fuel (83% diesel + 15% water + 2% surfactants (span 80 (Sorbitane Monooleate) and tween 80 (Polyoxyethylene sorbitane monooeate)). They experimented evaporation rate analysis in a hot plate setup and showed the high evaporation rate for emulsion fuel compared to neat diesel for the addition of nano particles and subsequemtly the working characteristics of the CI engine were improved substantially by the addition of nano particles.

Qi *et al*. [41] conducted experiments and evaluated the combustion and emission characteristics of single cylinder DI diesel engine by using neat biodiesel, ethanol - soybean methyl ester (biodiesel) - water micro emulsions blends at engine operating speed of 1500 rpm. They found that BSFC was increased for the micro emulsions against that of neat biodiesel due to lower calorific value of the micro emulsions and brake specific energy consumption (BSEC) was decreased for the micro emulsions due to improved combustion at all loads. They also found that the emissions of HC and CO were increased for the micro emulsions against those of neat biodiesel at low and medium engine loads and no significant change in HC and CO emissions for all the blends at high loads. NO_x emission was decreased for the micro emulsions under all engine loads and smoke emission was decreased for the micro emulsions against that of neat biodiesel at high engine loads. Qi *et al*. [42] studied the combustion and emission characteristics of rapeseed oil based biodiesel - diesel-ethanol micro emulsions in a two-cylinder, naturally aspirated, four stroke, water-cooled, 17:1 compression ratio, DI diesel engine at a engine speed of 1500 and 1800 rpm. They found that BSFC was increased for the micro emulsions under all conditions against that of neat diesel and BSFC depends on the fuel density, viscosity and heating value of fuel. They also found that NO_x emission was increased with the increasing loads due to more amount of fuel injected into the cylinder causes higher gas temperature and NO_x emission was decreased with the increase in engine speed due to the shorter residence time of nitrogen at high temperature. They further found that smoke emission was increased with the engine load and smoke emission was decreased for the micro emulsions at high engine loads against that of neat diesel.

Effect of oxygenate additives on the working characteristics

Oxygenated fuels are advantageous to the reduction of smoke or particulate matter emissions in diesel engines. Many experiments proved that smoke emissions from the engine can be reduced when oxygenated fuels are blended with diesel fuel. The smoke concentration is decreased regardless of the types of oxygenate additives and revealed that the reduction of smoke is strongly related to the oxygen-content of blends. CO and HC concentrations decrease with the increase of oxygen mass fraction in the blends. Oxygenates such as 2-methoxyethyl acetate (MEA), dimethoxymethane (DMM), diglyme (DGM), dimethyl carbonate (DMC), diethyl carbonate (DEC), diethyl adipate (DEA), ethanol, 1, 1-diethoxyethane, Pentadecane (PD), triacetin ($C_9H_{14}O_6$) etc. can added to

Table-4. Properties of DME,DMC,DMM, MEA and Diesel (Yanfeng *et al*. [41]).

	DME	**DMC**	**DMM**	**MEA**	**Diesel**
Molecular formula	CH_3OCH_3	$CH_3OCO_2CH_3$	$CH_3OCH_2OCH_3$	$CH_3COOCH_2OCH_3$	CxHy
Boiling point	-24.9	90-91	42.3	145	180-360
Cetane number	55-66	35-36	<30		40-55
Lower heating value,MJ/Kg	27.6	15.78	22.4	21.1	42.5
Density, kg/m^3	667	1075	859	1010	828
Energy density, J/mm^3	18.41	16.96	19.24	21.31	35.19
Oxygen content, wt %	34.8	53.3	42.1	40.7	0

the diesel/ biodiesel to obtain excess oxygen content during combustion that may move to better combustion and reduced emissions

Yanfeng *et al*. [43] conducted experiments to evaluate the diesel engine by using 2-methoxyethyl acetate (10, 15 and 20%) to diesel fuel. They reported that the maximum cylinder pressure was decreased for the oxygenated blends, while the ignition delays and the combustion duration became shorter. They also reported that indicated thermal efficiency was increased by 2.5, 5.7 and 7.1% with the oxygenated blends MEA10, MEA15 and MEA20 respectively at 2000 rpm and 0.5 MPa BMEP against that of neat diesel because MEA helps to accelerate the combustion process. But the level of pollutants, smoke density was decreased by more than 50 % with the oxygenated blends MEA and the emissions of HC and CO were decreased with the increase of MEA in the blends. However, the oxygenated blends have no effect on the NO_x emission. Properties of oxygenates and diesel given in the Table-4. Ren *et al*. [44] carried out an experimental investigation to evaluate the combustion and emissions of a D.I. diesel engine by using oxygenates (dimethoxymethane (DMM), diglyme (DGM), dimethyl carbonate (DMC), diethyl carbonate (DEC), diethyl adipate (DEA) and ethanol). They reported that the exhaust emissions were decreased for the diglyme blends against that of the other five oxygenate blends due to diglyme has the higher cetane number than the others. They also reported that smoke emission was decreased with all the oxygenate additives because smoke was strongly related to the oxygen-content of blends.

Frusteri *et al*. [45] carried out an experimental investigation to evaluate the emissions on diesel engine by using bio-derived oxygenated compound (1, 1-diethoxyethane) and the additive was obtained from bio-ethanol by means of an acid-catalysed process. They found that BSFC was slightly higher for the oxygenated blend than that of neat diesel fuel due to the lower heat content of the oxygenated additive. They also found that an insensitive effect on HC, CO and NO_x emissions with the using of 1, 1-diethoxyethane. On the other hand, smoke was greatly decreased with the oxygenated blends against that of neat diesel. Byun *et al*. [46] conducted experiments to evaluate the emissions on the diesel engines with the capacities of 632 and 11,149 cc. They reported that smoke was greatly decreased with the gas separation membranes used in the diesel engines. Polystyrene content has a great impact on the membrane performance and the optimized polystyrene contents in the final membrane were 50 wt. %. They reported that smoke emission was remarkably decreased by 35-73% with the usage of oxygen separation membrane in both the diesel engines. The oxygen concentration in the inlet air affects the composition of the emission gases. HC emission was decreased and NO_x emission was increased with the increase of oxygen concentration.

Chen *et al*. [47] carried out experiments to evaluate the performance and emissions characteristics of a diesel engine by using neat diesel, E10B (10% of ethanol + 5% of ester + 85% of diesel), E20B (20% of ethanol + 10% of ester + 70% of diesel) and E30B (30% of ethanol + 10% of ester + 60% of diesel) blends. They observed that torque was decreased by 6 - 7% for every 10% (by volume) ethanol added to the diesel, whereas the BSFC was increased for the same. But the level of pollutants, HC emission was apparently decreased with the ethanol-ester-diesel blends. CO emission was increased with the ethanol-ester-diesel blends at low and medium loads and decreased at high and full loads. Smoke and particulate matter (PM) was decreased significantly with the increase of oxygen content in the fuel. NO_x emission was slightly increased with the blended fuels against that of neat diesel fuel. Venkateswara Rao *et al*. [48] studied the effect of oxygenated additive as triacetin ($C_9H_{14}O_6$) on the performance and emission characteristics of diesel engine by using neat diesel, coconut oil methyl ester (COME biodiesel) and COME + triacetin (5, 10, 15, 20 and 25% by volume) blends. They found that BSFC was increased with the increase in triacetin percentage against that of neat biodiesel due to low calorific value of triacetin. They also found that the maximum emissions were decreased with 10% triacetin blend with biodiesel against that of neat diesel and COME biodiesel.

Effect of antioxidant additives on the working characteristics

Oxidation stability is an indication of the degree of oxidation, potential reactivity with air, and can determine the need for antioxidants. Antioxidants are added to increase the oxidation stability during long term storage. It is quite possible that these additives may affect the clean burning characteristics of biodiesel. Some of the most commonly used antioxidants are p-phenylenediamine, ethylenediamine, α tocopherol, butylated hydroxytoluene and L-ascorbic acid. Structures of antioxidants given in the Table-5.

Varatharajan *et al*. [49] investigated and compared the effect of antioxidant additives on NO_x emissions on Kirloskar TAF-1, four stroke, water cooled, single cylinder diesel engine [4.4 kW at 1500 rpm] by using jatropha methyl ester. The antioxidant additives namly L-ascorbic acid, α tocopherol acetate, butylated hydroxytoluene (BHT), p-phenylenediamine and ethylenediamine were added to biodiesel and tested. They observed that the BSFC was increased with L-ascorbic acid, BHT and a-tocopherol against that of neat biodiesel due to incomplete combustion, whereas BSFC was slightly decreased with the ethylenediamine and p-phenylenediamine antioxidant jatropha methyl ester against that of neat biodiesel due to friction reduction properties of the amines. They also observed that mean NO_x reduction was found as 43.55, 32.73, 17.84, 14.51 and 5.86% for p-phenylenediamine, ethylenediamine, a-tocopherol, butylated hydroxytoluene, and ascorbic acid respectively relative to neat biodiesel at 0.025%-m concentration. Further, that HC and CO emission were increased with the addition of antioxidants. Similar experimental study was presented by Varatharajan and Cheralathan [50] and they analyzed the effect of p-phenylenediamine derived aromatic amine antioxidants on NO_x reduction by using soybean biodiesel. The antioxidant additives were N, N′-diphenyl-1, 4-phenylenediamine (DPPD) and N-phenyl-1, 4-phenylenediamine (NPPD) added to biodiesel and tested. They found that NO_x emission was significantly decreased with the addition of antioxidants but the other emissions as HC, CO and smoke were increased. Balaji and Cheralathan [51] investigated the effect of antioxidant additive (L-ascorbic acid 100- 400 mg) on NO_x emissions in a diesel engine by using methyl ester of cottonseed oil (MECSO)and reported that NO_x and HC emissions were decreased with the addition of antioxidant methyl ester of cottonseed oil.

Kivevele *et al*. [52] investigated the experimental effects of antioxidants on the oxidation stability of a four cylinder TDI diesel engine by using croton oil methyl ester (biodiesel). They tested the oxidation stability on croton oil methyl ester (COME) with three synthetic antioxidants as 1, 2, 3 tri-hydroxy benzene (Pyrogallol, PY), 3, 4, 5-tri hydroxyl benzoic acid (Propyl Gallate, PG) and 2-tert butyl-4-methoxy phenol (Butylated Hydroxyanisole, BHA). They reported that the effectiveness of the antioxidants was in the order of Pyrogallol, Propyl Gallate and Butylated Hydroxyanisole. Kivevele *et al*. [53] investigated the engine performance, exhaust emissions and combustion characteristics of a four cylinder TDI diesel engine by using neat diesel, croton oil methyl ester (biodiesel), B100 + PY1000 (croton biodiesel + 1000 ppm of an effective antioxidant) and B20 (20% of croton biodiesel + 80% of neat diesel). They have found that the BSFC was decreased with antioxidants added biodiesel against that of biodiesel fuel without antioxidants, but both were higher than that of neat diesel and the maximum BTE was obtained as 37.83, 37.34, 37.33 and 36.88% for neat diesel fuel, B20, dosed biodiesel (B100 + PY1000) and B100 respectively at full load. There was no change in the combustion characteristics with the addition of antioxidants in biodiesel in the CI engine. But the level of pollutants, HC emission was decreased with all the samples at 50% and 75% loads and HC emission was lowest with biodiesel and followed by B20 and neat diesel and no change in the PY antioxidant added biodiesel. CO emission was increased for the blends such as B20, B100 and B100 + PY1000 against that of neat diesel at full load, but no differences were found between biodiesel sample with or without antioxidants. Smoke emission was decreased with the biodiesel samples against that of neat diesel due to its oxygenated nature. NO_x emission was increased with B100 + PY1000 by 1.5% against that of B100 at full load, but decreased at intermediate loads; however, both were increased against that of neat diesel. Obadiah *et al*. [54] studied the impact of various synthetic phenolic antioxidants on the oxidation stability and storage stability of Pongamia biodiesel (PBD). The antioxidants were butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), tert-butylhydroxyquinone (TBHQ), Gallic acid (GA) and pyrogallol (PY) added to PBD and tested. They found that pyrogallol (PY) was the best antioxidant and showed the improvement in the oxidation stability of PBD.

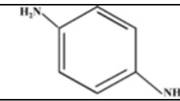
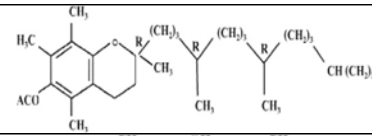
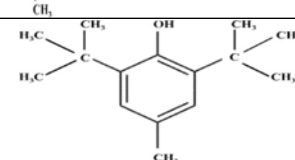
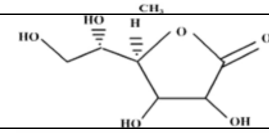
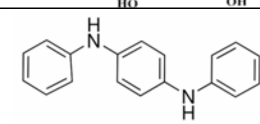
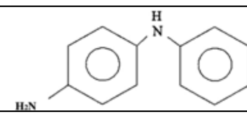
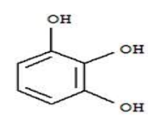
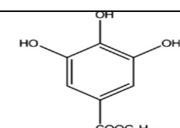
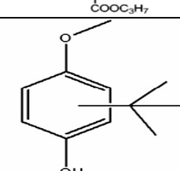
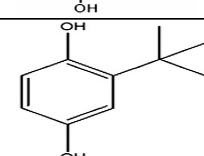
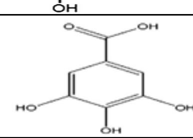
Effect of alcoholic additives on the working characteristics

Using of alcohols provides an attractive alternative fuel for internal combustion engines. Moreover, alcohol can be obtained from bio-refineries, thus reducing the consumption of fossil fuels. Some of the alcoholic additives such as methanol, ethanol,propanol, butanol and pentanol are considered in this paper.

Zhu *et al*. [55] carried out experiments to evaluate the performance and emissions on CI engine by using neat diesel fuel, biodiesel, and ethanol - waste cooking oil (biodiesel) blends (BE). They observed that the engine performance was improved with 5% ethanol in biodiesel (BE5) against that of neat diesel fuel. They also observed that HC, CO and PM emissions were decreased and NO_x emission was increased with the biodiesel against that of neat diesel fuel. Further, HC and CO emissions were slightly decreased with the BE5 against that of biodiesel in all test conditions.

Aydin and Ilkilic [56] studied and compared the performance and emissions of single cylinder; four strokes DI diesel engine by using fuel blends B20 (20%)

Table-5. Chemical structure of antioxidants.

Investigators	Antioxidant	Chemical Structure
Varatharajan *et al*. [49]	p-phenyle-nediamine	
	Ethylene-diamine	
	α-Tocopherol acetate	
	Butylated hydroxytoluene (BHT)	
	L-ascorbic acid	
Varatharajan and Cheralathan [50]	DPPD (N,N′-diphenyl-1,4-phenylenediamine)	
	NPPD (N-phenyl-1,4-phenylenediamine)	
Kivevele *et al*. [52]	Pyrogallol (PY)	
	Propyl gallate (PG)	
Obadiah *et al*. [54]	Butylated hydroxyanisole (BHA)	
	Ttert-butylhydroxyquinone(TBHQ)	
	Gallic acid (GA)	

of sunflower biodiesel + 80% of diesel), BE20 (80% of sunflower biodiesel + 20% of ethanol) and neat diesel fuel. They compared that the BTE was increased with BE20 against that of neat diesel fuel and B20 due to better combustion, and additional lubricity of biodiesel that contained in BE20. The BSFC was decreased with BE20 fuel against that of B20 and almost the same as that of neat diesel fuel. They also found that exhaust emissions were decreased with BE20 fuel. Sivalakshmi and Balusamy [57] carried out experiments to study the performance and emissions of a single-cylinder, four-stroke, naturally aspirated, direct-injection diesel engine by using neat diesel fuel, neem oil and its blends (5, 10, 15 and 20% volume) with ethanol, 1-propanol, 1-butanol and 1-pentanol. They found that the BTE was decreased with neat neem oil and its blends of different alcohols against that of neat diesel and increased with the neem oil-alcohol blends against that of neat neem oil. But the level of pollutants in the exhaust gases (HC, CO and smoke) were decreased with the neem oil-alcohol blends against that of neat neem oil at higher loads. Further they found that, NO_x emission was slightly decreased with the neem oil-alcohol blends except for the neem oil-ethanol blend against that of neat neem oil. Ma *et al*. [58] studied the combustion and emission characteristics of DI diesel engine by using neat diesel; diesel-propane (6 and 14% by volume) blends at operating speeds of 1400 and 2200 rpm. They revealed that thermal efficiency was increased with the proportion of propane in the blends and the maximum rate of pressure rise, maximum rate of heat release and maximum mean combustion temperature were increased with the increase in propane percentage in the diesel-propane blends. But the level of pollutants in the exhaust gases (HC, CO and smoke) were decreased where as NO_x emission was increased with the diesel-propane blends. Fernandez *et al*. [59] studied the performance of three-cylinder, four-stroke, water-cooled, compression ratio 18.5, DI diesel engine (Perkins model AD 3-152) by using different 1-butanol / diesel (upto 30% butanol) and 1-pentanol / diesel (upto 25% pentanol) fuel blends. They reported that BSFC was decreased for the butanol blends compared to that of pentanol blends and neat diesel fuel. They also reported that fuel properties of butanol and pentanol showed lower heating value, self-ignition temperature, vaporization latent heat, density, cetane number closer to those of diesel fuel, compared to those of ethanol and methanol.

Effect of biodiesel on the working characteristics

Biodiesel is defined as alkyl esters of fatty acids, obtained from the transesterification of oils or fats, from plants or animals, that have properties similar to petroleum diesel, causing their development as alternative fuels and extenders for combustion in diesel engine. It has an engine performance comparable to that with conventional diesel and could be used pure or blended with diesel. Devan and Mahalakshmi [60] studied the performance and emissions of single cylinder diesel engine by using neat diesel, methyl ester of paradise oil and eucalyptus blends (Me20-Eu80, Me30-Eu70, Me40-Eu60 and Me50-Eu50). They found that BTE was maximum (31.42%) with the Me50-Eu50 blend and is comparable to that of the other blends at full load. They also found that the exhaust emissions were decreased by 34.5, 37 and 49% for HC, CO and smoke respectively and NO_x was increased by 2.7% with the Me50-Eu50 blend at full load against that of neat diesel fuel. Huang *et al*. [61] carried out experiments and compared the performance and emissions of diesel engine by using neat diesel and dimethyl ether (DME). They reported that the equivalent BSFC of DME was better than that of diesel fuel for the engine speed of less than 1500 rpm and full load; where as the equivalent BSFC of DME is poorer than that of diesel fuel at speed above 1500 rpm. But the level of pollutants, HC and NO_x emissions were decreased and smoke-free, whereas CO emission was slightly increased with the DME engines at all test range of loads and speeds comparable to that of neat diesel fuel. Sivalakshmi and Balusamy [10] carried out experiments to evaluate the performance and emission characteristics by using diethyl ether as additive to biodiesel (Neem oil methyl ester). They found that BTE was increased with the BD5 (5% diethyl ether blended biodiesel) compared to that of neat biodiesel. They also found that peak cylinder pressure and heat release rate were more for BD5 than those of neat biodiesel. In addition they have shown that CO and smoke emissions were decreased whereas NO_x and HC emissions were increased for BD5 blend.

Suresh kumar *et al*. [62] carried out experiments to evaluate the performance and emissions on single cylinder four-stroke, water-cooled compression ignition engine that was fueled with Pongamia Pinnata Methyl Ester (PPME) and its blends (B20, B40, B60, B80 and B100) and compared the results of neat diesel at a constant speed (1500 rpm). They indicated that PPME blends up to 40 % (B40) was shown better engine performance (BSFC and BSEC) and lesser emissions. Chattha *et al*. [63] carried out the experiments and evaluated the performance and emissions of a direct injection, air cooled, CI engine fueled with Pongamia Pinnata Methyl Esters (B50 and B100) compared to diesel at engine speed of 3600rpm. They prepared the biodiesel from Pongamia Pinnata oil by transesterification with methanol. They reported that BSFC was increased with biodiesel compared to that of diesel due to low calorific value of biodiesel. They also reported that exhaust emissions as HC, CO and smoke were decreased and NO_x emission was increased. On the similar study by Sukumar Puhan *et al*. [64]; studied and evaluated the performance and emissions of CI engine by using Mahua Oil Ethyl Ester (MOEE) compared with the diesel and tested at 1500 rpm. They prepared the biodiesel from Mahua oil by transesterification using sulfuric acid (H_2SO_4) as a catalyst. They reported that BSFC, EGT were increased with the biodiesel compared to that of neat diesel and noted BTE as 26.42% for MOEE where as 26.36 % for diesel. Regarding the exhaust emissions as HC, CO, smoke and NO_x were decreased by 63, 58, 70 and 12% respectively for MOEE compared with that of neat diesel. Raheman and Ghadge [11] studied the performance and emissions of a Ricardo E6 CI engine fueled with mahua oil and its blends (B20, B40, B60, B80 and B100) with high speed diesel. They found that BTE was decreased with increase in the proportion of biodiesel in the blends and the maximum BTE was obtained as 25 and 24% for B20 and B40 respectively and corresponding value of high speed diesel was 24%. They also found that exhaust emissions CO and smoke were decreased while NO_x emission was increased with increase in percentage of mahua biodiesel in the blends. Deepak Agarwal and Avinash Kumar Agarwal [65] carried out experiments and compared the performance and emissions of a naturally aspirated DI diesel engine by using Jatropha oil (preheated and blends), unheated Jatropha oil with neat diesel at a speed of 1500 rpm. They pointed that BSFC and EGT for unheated Jatropha oil were more in the case of neat diesel than those of preheated Jatropha oil. They also pointed out that the BTE was decreased with the unheated Jatropha oil compared to preheated Jatropha oil and neat diesel. The emissions such as HC, CO and smoke were increased with unheated Jatropha oil compared to that of neat diesel and these emissions were found to be nearer to same for the neat diesel and preheated Jatropha oil.

Exhaust gas treatment techniques

The recirculation of exhaust gas through an EGR (Exhaust Gas Recirculation) valve into the intake manifold where it mixes and dilutes the incoming fresh air and it is an effective method to reduce NO_x emission. EGR amount can be calculated from the following expression as sown in equation (1).

$$\%\ EGR = \frac{\text{(Mass of air admitted without EGR - Mass of air admitted with EGR)}}{\text{(Mass of air admitted without EGR)}} \quad (1)$$

Pradeep and Sharma [66] studied the effect of EGR on a NO_x emission by using Jatropha biodiesel in a compression ignition engine. They reported that the NO_x emission was decreased by 15% by using EGR without much adverse effects on the performance and other emissions. Prasad Rao and Kaleemuddin [67] carried out experiments to evaluate the performance and emissions on CI engine with variable timing fuel injection cam (VIC) and EGR. Significant reductions in NO_x and smoke emission levels were found. Combined effect of VIC with 7% EGR could reduce the CO by 88%, HC + NO_x by 37% and PM emissions by 90%. Hebbar and Bhat [68] investigated the effect of hot EGR and ethanol on a NO_x emission on Kirloskar AV1 diesel engine (3.7 kW at1500 rpm) and reported that NO_x emission was decreased along with marginal loss of efficiency. HC and smoke emissions were increased with the cooled and hot EGR. They also reported that using the addition of Ethanol along with EGR recovered the efficiency and lower the emissions.

CONCLUSIONS

The following conclusions are drawn based on the review.

- The performance, combustion and emission characteristics of compression ignition engines are appreciably influenced by injection pressure, injection timing and compression ratio.
- The working characteristics of compression ignition engines significantly improved by selecting proper fuel additives.
- Thermal barrier coatings and exhaust gas recirculation systems are the promising techniques for improving the working characteristics of CI engine.

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