Bio-fuel variants for use in CI engine at design and off-design regimes: An experimental analysis

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ABSTRACT

In this work an attempt has been made to study the ester based fuel variants derived from edible and inedible oil sources for identifying the most appropriate fuel variant and operating mode for running a CI engine based on performance and emission parameters. The twenty four fuel variants tested included esters obtained from the edible sunflower oil, inedible pongamia oil, and their higher and lower proportional blends with diesel. Besides, several other fuel variants obtained from the emulsification of water-in-ester (W/E) with different water proportions have been tested. Basing upon three operational variables, namely, injection timing, injection pressure, and load, comparisons are made in aspects of smoke emissions, NO_X emissions, BSEC, and exhaust gas temperatures at the best injection timing. 21.5°, 23°, 24.5° and 27.5° bTDC as the four injection timings and 190, 220 and 250 bar as three injection pressures are considered for the overall study. The 264 sets of experiments conducted with these combinations, focussing on the full and partial load characteristics of the engine, show that both sunflower and pongamia oil esters exhibited similar characteristics in their engine performance, and in both the cases the best BSEC occurred with 220 bar injection pressure for most of the fuel variants, and for straight fuels the ideal injection timing found to be slightly retarded (1.5° crank angle) compared to diesel. However, 24.5° bTDC, normal for the engine, was found to be the most appropriate for the lower blends like B2 (2% ester by volume), B5 and emulsion with 10% water proportion.

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1. Introduction

A number of research investigations show the use of vegetable oil-based fuels in CI engine, besides identifying the benefits and problems associated therewith [1–4]. The negative effects of its use are reduced or eliminated by transesterification of oil [5–10]. The use of esters for running a CI engine falls under two categories namely; use of ester blended with diesel and complete replacement of diesel. In the first, it is done either by replacing a small quantity of diesel with ester, resulting in little or no drop in efficiency but with a substantial drop in emission, or by replacing a large quantity of diesel with ester leading to substantial drop in emission, but with a fall in efficiency. In the second, the aim is to improve the emission, while allowing for certain drop in efficiency.

Use of ester in engines requires large quantities of vegetable oils. The production of ester will, therefore, affect the demand and supply for human consumption, thus compelling the need for substituting it with inedible oil. This study compares the performance and emission characteristics associated with the use of esters produced from both sunflower oil (edible) and pongamia oil (inedible). The study is intended to quantify the benefits, if any, associated with pongamia oil ester over the sunflower oil ester. Until the country develops capability for surplus production of edible/inedible oil, the use of esters should perforce be restricted to diesel and ester blend for extending the diesel usage. In this work, blends have been categorised as lower and upper blends. The blends up to 10% are considered lower blends and higher than that as the upper. In both categories, blends of edible and inedible esters are considered for the study.

The combustion in a diesel engine is a complex process. It depends on many causes like mixing of air and fuel, pressure and timing of fuel injection. A reason for the formation of exhaust pollutants is insufficient combustion in the engine cylinder. Fuel properties also play a significant role in formation of exhaust pollutants [11]. Various investigations have reported that cetane number (CN) does affect exhaust emissions [12]. The ignition delay period is reduced by increasing the CN, giving an opportunity for the stable running of the engine. The increase in injection pressure makes the fuel particles finer and thus reducing the ignition delay [11]. It also reduces smoke, but increases CO emission. The ester produced from oil has higher cetane number than that of diesel. These factors have proved to produce change in the performance and emission characteristics; therefore, keeping these in view, a study

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has been performed for various injection pressures (190, 220 and 250 bar) and injection timings (21.5°, 23°, 24.5° and 27.5° bTDC).

Use of vegetable oil ester is known to lead to higher NO_X, partly due to the presence of oxygen in the fuel. The use of water along with diesel and its effect at reducing NO_X have been dealt with in Ref. [13–15]. In general, it has been concluded therein that the presence of water vapour in reactants has a beneficial effect on the exhaust emissions. During combustion, the vapourised water reduces the flame temperature and changes the chemical composition of the reactants, leading to higher OH radical concentration controlling the NO_X formation rate and soot oxidation, and diluting the rich zones in the combustion chamber. Water may be added to fuel in any one of the following ways: (i) by injecting continuously into the air stream via a single point system or periodically through the intake valves via a multi-point system [14], (ii) by injecting directly into the cylinder through a separate nozzle, or introducing to fuel within the injection nozzle in the absence of fuel injection, (iii) by stratified fuel–water injection, or (iv) through the preparation of stabilised water-in-ester emulsion (W/E) [15]. In this work, emulsion produced from ester with water has been used as an alternative fuel for diesel engine. This study aims at quantifying NO_X reduction and other emissions in diesel engine by the use of W/E emulsion. However, excess use of water over a long period is detrimental to the engine. Hence, in this work a very small amount of water is tried (2.5%, 5%, 7.5% and 10%). Further to investigate some physical effects of water present in fuel during combustion in a diesel engine, it is important to consider major injection parameters that have a strong effect on the primary spray droplet size and distribution over the combustion chamber. The primary spray fuel droplets are further divided into a vast number of smaller fuel droplets as a result of explosive vaporisation caused by the rapid heating of water dispersed within the individual fuel droplets [13]. The efficiency of secondary atomisation depends on injection pressure because it determines droplet size in W/E emulsion. Hence, experiments have been conducted at various injection pressures and various injection timing for W/E emulsion. Even though the use of water with vegetable oil in emulsion form, for use in CI engine, could be efficient, in this work, experimentation is restricted to emulsion of water in ester in addition to other fuel variants.

2. Experimental facilities

Fig. 1 shows a general scheme of engine test bench and the experimental apparatus used in the work. A commercial single cylinder, 4-stroke, naturally aspirated, water cooled, direct injection diesel engine is utilised as the experimental unit whose specifications are listed in Table 1.

The fuel and air flow rates are manually obtained. An infrared absorption gas analyser is used to measure NO_X, CO_2, CO, O_2 and HC emissions at the tail pipe. The particulate emission is measured as opacity reading that is proportional to the total light extinction across the exhaust gas stream, and is determined by a smoke meter MRU OPTRON 1600. The details of instrumentation are given in Table 2. A data acquisition system directly records instantaneous engine parameters in MS Excel.

3. Fuel characteristics

3.1. Determination of physical and chemical properties

The viscosity of the esters is determined using Saybolt viscometer as per the ASTM standard at 40 °C. Density is also determined at the same temperature. The flash and fire points are determined using Cleveland open cup tester. An industrial thermometer determined the boiling point. All the experiments were repeated three times to establish the average value. The saponification number (SN) and iodine value (IV) were determined using Eqs. (1) and (2) [16], respectively

$$SN = \sum (560 \times A_i)/MW_i \qquad (1)$$

$$IV = \sum (254 \times D \times A_i)/MW_i \qquad (2)$$

where A_{ii} is the percentage, D is the number of double bonds and MW_i, the molecular mass of each component. The cetane number (CN) was calculated by Eq. (3) [16]

$$CN = 46.3 + 5458/SN - 0.225 \times IV \qquad (3)$$

3.2. Comparison of physical and chemical properties

When compared with physical and chemical properties of ester of sunflower oil, pongamia ester show that its normal boiling point (NBP) was 2.5% lesser, flash point 3.5% more, kinematic viscosity 4.8% more, density 0.2% lesser, saponification number 6.9% lesser, IV 40% lesser, CN value 37.5% more, and yield was lesser by 2.3%.

The calculated value of CN for sunflower oil ester is only slightly more (about 7.5%) than that of diesel, but it is very high (about 37% more) for pongamia ester. The ASTM standard for CN for fuel used in CI engine is 40 on the lower limit and 65 for the upper, and for
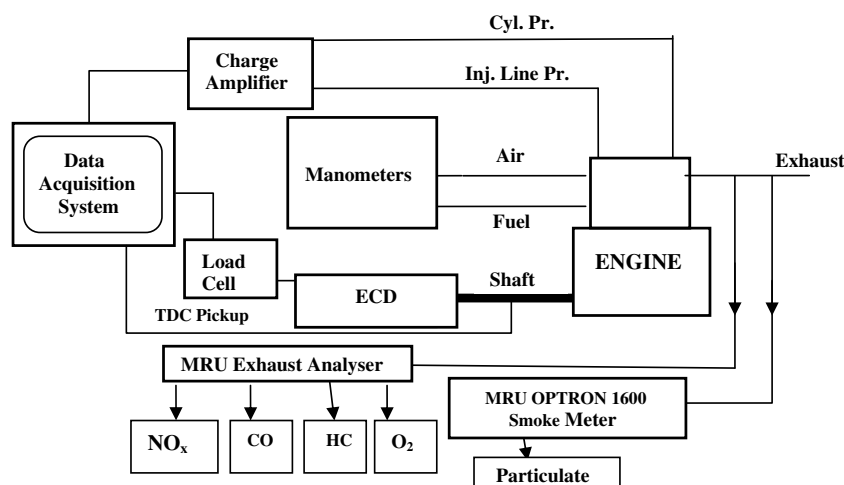

Fig. 1. Schematic diagram of engine test bed, instrumentation and data logging system.

Table 1
Specification of the test engine and accessories

No. of cylinders	1	Injection pump type	Jerk-pump with rack and pinion
Rated speed	1500	Combustion chamber	Bowl in the piston
Compression ratio	17.5	Dynamometer type	Eddy current
Normal injection pressure	190 bar	Pressure sensor	Peizo electric
Maximum rated power	7 hp	Temperature measurement	Thermocouple
Cylinder bore	87.5 mm	Valve timing:	
Stroke	110 mm	Inlet valve open	10° before TDC
Clearance volume	41.09 mm^3	Inlet valve close	38.74° after BDC
Total swept volume	661 mm^3	Exhaust valve open	31° before BDC
Type of cooling	Water cooled	Exhaust valve close	12° after TDC
Normal injection timing	24.5° bTDC		
Injector type	Single multi-jet injector		

Table 2
Specification of instruments used for measurement of cylinder pressure, exhaust temperature, smoke meter, and exhaust gas analyser

Item	Resolution	Range	Calibration
Cylinder pressure sensor	0.0069 bar	0–344.75	3% deviation
EGTS	0.01 °C	0–1000 °C	0.5% deviation
Smoke meter	0.01(HN)	0–100 (HSN)	1% deviation
Exhaust gas analyser	CO – 0.01%	0–10%	0% deviation
	NO$_X$ – 1 ppm	0–500 ppm	0.8% deviation
	O$_2$ – 0.01%	0–22%	0.2 deviation
	CO$_2$ – 0.1%	0–16%	0.8% deviation

IV, 120 is the upper limit [16]. The pongamia ester has 40% lesser IV value than that of sunflower ester. However, the IV value of pongamia ester is well within the ASTM standard. The ASTM standard for NBP is $\leqslant 360\,°C$. Both the esters have almost the same NBP, and are way below ASTM standard.

3.3. Comparison of GLC spectra for esters

The successful commercialisation of biodiesel in the future depends on a variety of parameters. One of them is fuel quality as defined in some European countries. The amount of contaminants (such as glycerol; mono-, di-, and triglycerides; and alcohol) present in the fuel after post-transesterification–purification is a major factor in determining fuel quality. Most analytical procedures, for determining biodiesel fuel quality, utilise gas chromatography (GC) [17]. The GLC spectra for the ester samples in this work are obtained from Sophisticated Analytical Instrument Facilities, Central Drug Research Institute, Lucknow, India. Fig. 2 is the GLC spectra of both ester samples showing only the important peaks. The peaks in the spectrum correspond to the various fatty acid compounds present in methyl ester of vegetable oil. The important fatty acids present in both fuels are shown in Table 3 along with the time of occurrence and area (percentage) under each peak. From Fig. 2 and Table 3, it is seen that, for some important peaks of various fatty acid constituents, the time of their occurrence and area are almost the same for both ester samples. However, if unsaturated fatty acids (oleic and lenoleic) are taken together, the sunflower ester has around 7% higher composition compared to the pongamia ester. This is the reason for difference in properties, especially the cetane number. Cetane number also depends
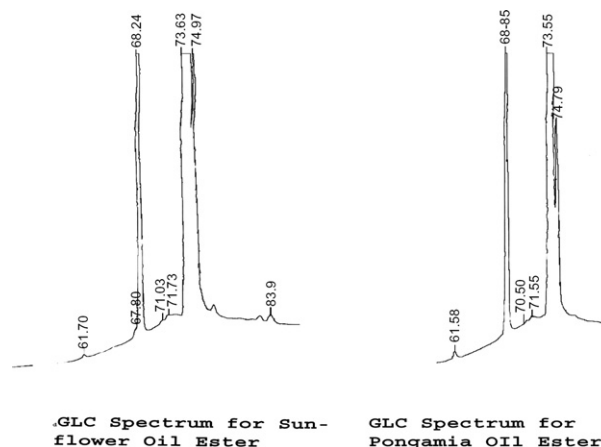

Fig. 2. GLC spectra for sunflower and pongamia ester obtained using Autosystem GC at SAIF, CDRI, Lucknow, India.

on the composition of saturated fatty (palmitic acid) [18]. In Table 3, the palmitic acid content is 11% more for pongamia ester compared to sunflower ester. Additionally, for storage, the ester with higher O/L ratio (oleic to lenoleic) needs to be considered. In the comparison, the sunflower ester is found be scoring over pongamia ester in that regard, as it has the ratio 4.6% higher than pongamia ester.

4. Scheme of experiment and experimental procedure

Table 4 gives the outline of experiments conducted. To validate the results, the experiments were repeated at selected points. For experiments with sunflower ester, sunflower ester–diesel blend and water-in-sunflower ester emulsion, many loads have been considered. However, because of its similarity in load–efficiency characteristics, for pongamia ester related experiments, the work was restricted to 50% and 100% loads. For overall comparison also, only these two loads were considered. At the beginning of each series of experiments (generally every morning when the experiments were started), the engine was run for half an hour on diesel for warming. Later, after changing over to new load, the engine was run for 3 min before recording the readings, the fuel flow measurement being performed manually. For taking the smoke-meter and exhaust emission readings, the exhaust gas was allowed to flow for the same duration of time before readings were recorded. The probe of the equipment was frequently cleaned for removing carbon deposits. A statistical analysis carried out for the exhaust analyser (NO$_X$), smoke meter, speed and fuel measurement (time for 10 cc of fuel consumption) indicated a standard deviation of 3.6 (mean value: 451), 1.5 (mean value: 39.53), 3.78 (mean value: 1401.3), and 0.25 (mean value: 28.3), respectively. Before the start of the experiment with new fuel variant, fuel of the previous experiment was completely purged from the fuel line, filter, fuel pump and fuel tank. For the emulsion experiments, the fuel tank was mounted on a magnetic stirrer, and the fuel was continuously stirred. The emulsion was prepared by first mixing 1% by volume of Tween 80 emulsifier in methyl ester produced from vegetable oil, and then adding distilled water to it while being stirred. The emulsion sample generally got separated in 45 min of standing. Thus, it was necessary to stir the emulsion continuously while fuelling the engine with it. The ester preparation was obtained by heating the mixture of vegetable oil and methoxide, which was prepared by mixing methanol (99% purity) and sodium hydroxide, in a reflex condenser at 70 °C for 2 h. The sodium hydroxide was used in the ratio of 1:4 molar quantities. The glycerol was then separated in a conical separator. The ester so obtained, with methanol

Table 3
Particulars of GLC Spectra for sunflower and pongamia ester with their composition and chemical formulae

Sunflower ester

Peak #	Time (min)	Area (%)	Imp. fatty acids	Structure
1.	61.704	0.030		
2.	67.800	0.300		
3.	68.236	23.34	Palmitic (C16:0)	$CH_3(CH_2)_{14}COOH$
4.	71.028	0.040		
5.	71.728	0.060		
6.	73.630	55.69	Linoleic (C18:2)	$\begin{cases} CH_3(CH_2)_4CH= \\ CHCH_2CH=CH \\ (CH_2)_7COOH \end{cases}$
7.	74.970	19.89		
8.	77.114	0.460	Oleic (C18:1)	$CH_3(CH_2)_7CH= CH(CH_2)_7COOH$
9.	77.114	0.460	Stearic (C18:0)	$CH_3(CH_2)_{16}COOH$
10.	98.115	0.150		

Pongamia ester

Peak #	Time (min)	Area (%)	Imp. fatty acids	Structure
1.	43.093	0.070		
2.	47.130	0.030		
3.	54.110	0.680		
4.	61.579	0.440		
5.	68.154	25.84	Palmitic (C16:0)	$CH_3(CH_2)_{14}COOH$
6.	70.495	0.000		
7.	71.551	0.030		
8.	73.554	52.47	Linoleic (C18:2)	$\begin{cases} CH_3(CH_2)_4CH= \\ CHCH_2CH=CH \\ (CH_2)_7COOH \end{cases}$
9.	74.785	17.92	Oleic (C18:1)	$CH_3(CH_2)_7CH= CH(CH_2)_7COOH$
10.	82.501	0.140		
11.	83.769	2.010	Stearic (C18:0)	$CH_3(CH_2)_{16}COOH$
12.	97.683	0.390		

Table 4
Scheme of experiments conducted in this work

Fuel variants	SME/diesel blends	Water-in-SME emulsion	PME/diesel blends	Water-in-PME emulsion
Blend used	2B, 5B, 10B, 20B, 40B, 60B, 80B, neat	2.5 W, 5.0 W 7.5 W, 10 W	2B, 5B, 10B, 20B, 40B, 60B, 80B, neat	2.5 W, 5.0 W 7.5 W, 10 W
Inj. pressure (bar)	190, 220, 250	190, 220, 250	190, 220, 250	190, 220, 250
Injection timing (° bTDC)	21.5, 23, 24.5, 27.5	21.5, 23, 24.5, 27.5	21.5, 23, 24.5, 27.5	21.5, 23, 24.5, 27.5
Load (% age)	0, 25, 50, 75, 100	0, 25, 50, 75, 100	50, 100	50, 100
No. of sets of expts.	96 sets	36 sets	96 sets	36 sets

(SME: sunflower methyl ester; PME: pongamia methyl ester; 2.5W: 2.5% water in emulsion).

and traces of glycerol in it, was washed five times with water to remove impurities and to bring down the pH value to neutral. Each time the ester was washed, it was kept standing in the separator for two hours. After five washes, the ester was separated, and upon heating to 80 °C, the remaining traces of dissolved water settled down at the bottom. The pH value was neutral on testing the sample. Earlier experience have proved that the thoroughly washed esters to have had lesser effect on the tubing than unwashed ester. During experimentation no major operational difficulties were experienced with any of the fuel variants.

5. Results and discussion

A comparison of performance and emission for various fuel variants and their relative benefits vis-à-vis diesel operation is attempted here.

5.1. Experiments with ester–diesel blend

The performance details at best BSEC for fuel variants obtained from the combination of diesel and ester are presented in Tables 5 and 6 for sunflower and pongamia ester, respectively. The values are relative to diesel fuel operation. It is seen in the tables that for neat fuel and blends, for both esters, the best injection timing is 23° bTDC (1.5° retardation) for blends higher than B20 at full load for all injection pressure ranges. This is attributed to higher bulk modulus of esters. This caused early injection and hence a slight retardation (1.5° CA) is recommended. However, for blends

with lesser amount of ester (lower blends), the best injection timing (based on best relative BSEC) is 24.5° bTDC, the same as that of diesel indicating diesel like behaviour. The fact that the peak pressures for such an injection timing occurred at the same location, as seen in Fig. 3 as that of diesel operation vouches for it. For part load, for the whole range of blends, the best injection timing is found to be 23° bTDC. In all the cases, the BSEC is higher than that of diesel and is upwards of 0.2–17%. The BSEC of sunflower ester or its blends, and diesel are closer to each other when compared to that of pongamia. Figs. 3 and 4 represent the nature of pressure histories at best BSEC values for various blends. Although the figures appear similar, the sunflower ester–diesel blend yield higher peak pressure than the pongamia ester–diesel blend, manifesting the fact itself to be a better fuel variant, either individually or combined. The difference in viscosity of SME and PME (4.8% higher for latter) appears to have taken a decisive role here. Fig. 5 shows the viscosity of SME/diesel and PME/diesel blends rising quite sharply even at low blends, hence, has profounder effects on performance parameters. Therefore, the difference in viscosity between the two esters at all blends is said to produce substantial difference in performance between two types of blends. In Figs. 3 and 4, it is seen that at higher blend proportions, a combination of injection pressure of 220 bar (which is higher than normal pressure for diesel) and injection timing of 23° bTDC is linked with the best BSEC both for SME/diesel and PME/diesel blend. However, the trend becomes less predictable as one move towards zero blends. At first, pressure continues to remain ideal at 220 bars with an injection timing of 24.5° bTDC, later becoming optimum at an injection pressure of 190 bar and timing of 24.5° bTDC. A visual observation of spray of the fuel showed longer length traversed for 220 bar and then reduced in length for 250 bar pressure. Besides, a marked difference in the dispersion is noted. Examination of injection pressure–time and gas pressure–time histories does not indicate any difference in delay period for different injection pressures. Therefore, dispersion of fuel, together with air entrainment was responsible for the behaviour observed. It can be deduced that while for 190 bar injection line pressure the dispersion is less and air entrainment is more, it is the other way for 250 bar. The injection line pressure of 220 bar has been able to produce the right balance of dispersion and air entrainment. Additionally, at 250 bar (60 bar more than normal diesel operation) the work required for injecting the fuel is substantially higher (pumping). The tables mentioned above show the NO_X values at the best BSEC and found to be lowest for 250 bar. This outcome could be attributed to poor combustion due to oxygen starvation due to lower penetration. At an injection pressure of 190 bar, the NO_X is more than that of diesel fuel operation. This result can be attributed partially to the fact that, even

Table 5
Comparison of relative performance for sunflower ester (neat) and sunflower/diesel blend for various injection pressures

	Best inj. timing		BSEC		NO_x		Smoke		Exhaust temp.	
	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load
Diesel/190	24.5	24.5	1 (11905 kJ/kWh)	1 (10688 kJ/kW h)	1 (530 ppm)	1 (735 ppm)	1 (16 HSN)	1 (49 HSN)	1 (355 °C)	1 (545 °C)
S.ester/190	23.0	23.0	1.167	1.062	1.128	1.315	0.623	0.796	1.000	1.030
S.ester/220	24.5	23.0	1.077	1.048	0.667	0.820	0.971	0.661	0.930	0.980
S.ester/250	23.0	23.0	1.162	1.087	0.644	0.544	2.810	0.608	0.675	0.990
S/D/80/190	23.0	23.0	1.102	1.024	1.397	1.670	0.428	0.508	0.990	1.020
S/D/80/220	24.5	23.0	1.052	1.016	0.557	0.910	0.770	0.614	0.950	1.030
S/D/80/250	23.0	23.0	1.047	1.028	0.543	0.631	1.000	0.514	0.950	0.970
S /D/60/190	23.0	23.0	1.103	1.018	1.453	1.630	0.823	0.430	0.990	0.990
S /D/60/220	23.0	23.0	1.063	1.011	0.720	0.870	0.881	0.671	0.940	1.020
S/D/60/250	23.0	23.0	1.062	1.038	0.623	0.611	0.780	0.491	0.930	0.980
S/D/40/190	23.0	23.0	1.104	1.002	1.474	1.540	1.071	0.373	1.010	0.980
S/D/40/220	23.0	23.0	1.081	1.004	0.860	0.741	1.100	0.746	0.940	0.990
S/D/40/250	23.0	23.0	1.019	1.041	0.726	0.590	0.680	0.469	0.910	0.990
S/D/20/190	23.0	24.5	1.090	1.024	1.474	1.780	0.728	0.814	1.020	1.030
S/D/20/220	23.0	23.0	1.081	1.005	0.860	0.904	0.885	0.681	0.940	0.970
S/D/20/250	23.0	23.0	1.023	1.014	0.726	0.515	0.721	0.451	0.940	0.970
S/D/10/190	23.0	27.0	1.127	1.026	1.562	1.343	0.571	0.569	1.000	1.000
S/D/10/220	23.0	24.5	1.089	1.004	0.772	0.902	0.743	0.763	0.900	0.996
S/D/10/250	23.0	21.0	1.045	1.014	0.590	0.620	0.622	1.154	0.950	0.964
S/D/5/190	23.0	23.0	1.107	1.031	1.422	1.080	0.579	0.627	1.000	1.000
S/D/5/220	23.0	24.5	1.079	1.021	0.923	0.921	0.971	0.679	0.920	0.960
S/D/5/250	23.0	24.5	1.200	1.056	0.662	0.810	1.136	0.690	0.945	0.980
S/D/2/190	23.0	24.5	1.137	1.031	1.227	1.404	0.557	0.644	0.960	1.060
S/D/2/220	24.5	24.5	1.087	1.042	0.945	0.787	0.657	0.751	0.950	1.070
S/D/2/250	23.0	24.5	1.077	1.045	0.720	0.630	0.914	0.783	0.930	0.970

Table 6
Comparison of relative performance for pongamia ester (neat) and pongamia ester–diesel blends at various injection pressures

|	Best inj. timing		BSEC		NO_X		Smoke		Exhaust temp.	
	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load
Diesel/190	24.5	24.5	1 (11905 kJ/kWh)	1 (10688 kJ/kWh)	1 (530 ppm)	1 (735 ppm)	1 (16 HSN)	1 (49 HSN)	1 (355 °C)	1 (545 °C)
P.ester/190	23.0	23.0	1.171	1.096	1.392	2.028	1.193	0.332	1.020	1.040
P.ester/220	24.5	23.0	1.270	1.088	1.022	1.500	1.907	0.502	0.920	1.010
P.ester/250	23.0	23.0	1.240	1.096	0.630	0.530	1.670	0.410	0.960	0.970
P/D/80/190	23.0	23.0	1.088	1.094	1.374	2.000	0.607	0.529	0.990	1.010
P/D/80/220	23.0	23.0	1.232	1.094	0.872	0.670	1.178	0.636	0.940	1.070
P/D/80/250	23.0	23.0	1.243	1.123	0.560	0.689	1.044	0.702	0.958	1.057
P/D/60/190	23.0	23.0	1.110	1.099	1.254	1.540	0.710	0.527	0.980	1.030
P/D/60/220	23.0	23.0	1.225	1.145	0.891	0.691	1.134	0.633	0.920	1.070
P/D /60/250	23.0	23.0	1.183	1.135	0.610	0.642	0.943	0.634	0.955	1.048
P/D/40/190	23.0	23.0	1.151	1.169	1.075	1.406	0.750	0.525	0.970	1.040
P/D/40/220	23.0	23.0	1.215	1.100	0.901	0.713	1.080	0.636	0.906	1.070
P/D/40/250	23.0	23.0	1.132	1.152	0.651	0.590	0.842	0.544	0.953	1.040
P/D/20/190	23.0	23.0	1.195	1.119	0.964	1.090	0.900	0.732	1.009	1.020
P/D/20/220	23.0	23.0	1.226	1.091	0.826	0.660	1.231	0.814	0.910	1.070
P/D/20/250	23.0	23.0	1.139	1.124	0.620	0.540	0.762	0.642	0.968	1.018
P/D/10/190	23.0	24.5	1.135	1.067	1.118	1.020	0.835	0.415	1.007	1.017
P/D/10/220	23.0	24.5	1.159	1.129	0.867	0.708	0.900	0.600	0.940	1.030
P/D/10/250	23.0	24.5	1.141	1.135	0.633	0.590	0.713	0.520	0.973	1.005
P/D/5/190	24.5	24.5	1.191	1.083	0.909	0.904	0.678	0.576	1.010	1.050
P/D/5/220	24.5	24.5	1.138	1.090	0.705	0.761	1.021	0.605	0.930	1.064
P/D/5/250	24.5	24.5	1.121	1.129	0.578	0.740	0.572	0.614	0.969	1.046
P/D/2/190	24.5	24.5	1.189	1.069	0.877	0.793	0.646	0.592	1.026	1.057
P/D/2/220	23.0	24.5	1.115	1.114	0.760	0.633	0.900	0.683	0.940	1.070
P/D/2/250	23.0	24.5	1.108	1.110	0.569	0.562	0.565	0.646	0.984	1.054
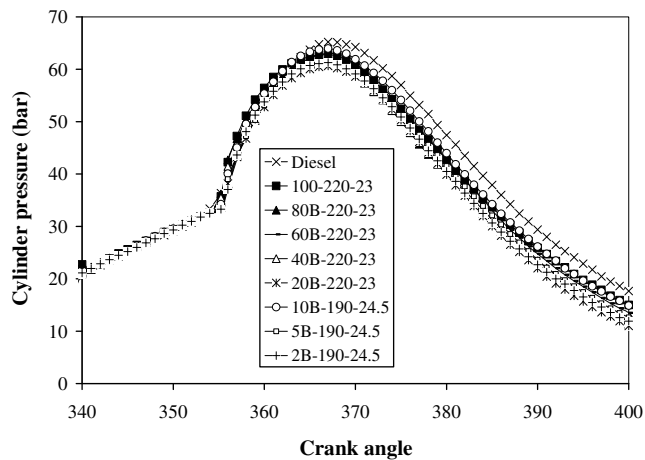
Fig. 3. Pressure histories for the best combination of injection pressure and injection timing for various blends of pongamia ester and diesel at best BSEC at full load (Legend: Blend (ester proportion in blend)-injection pressure-injection timing).
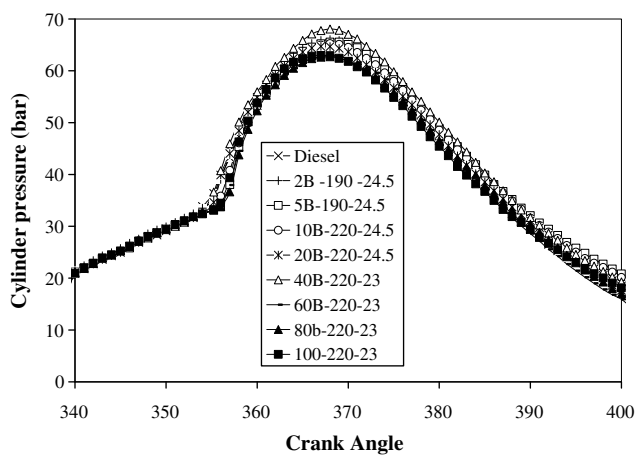

Fig. 4. Pressure histories for the best combination of injection pressure and injection timing for various blends of sunflower ester and diesel at best BSEC for full load (Legend: blend injection pressure-injection timing).
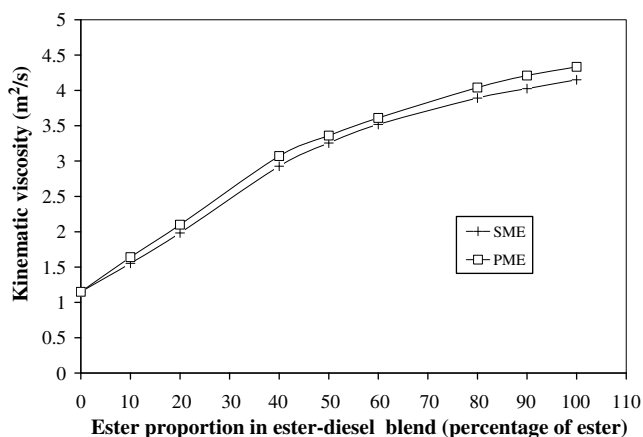

Fig. 5. Variation in viscosity with blend for sunflower ester–diesel blend.

though considered as a whole, oxygen supplied by the fuel is insignificant, locally, at the point where fuel droplets are present; this extra oxygen could have profounder effects on the combustion.

The emission of smoke is lesser than that of the diesel operation for any blend proportion and blend type at all the injection pressures. The smoke emission depends on peak soot concentration during combustion, fuel distribution, and oxidation of soot during exhaust stroke [11]. Therefore, the injection pressure which affects the fuel distribution, the injection timing which affects the fuel paralysis, which in turn affecting soot concentration, and fuel–oxygen which affects both soot concentration and its oxidation, are important factors affecting the smoke emission. It is speculated that the presence of fuel–oxygen in the core of droplet has caused lower smoke for blends when compared to diesel. From Tables 5 and 6, it is found that in going from higher to lower blend the trend is towards increased smoke. This behaviour could be attributed again to the presence of built-in oxygen molecules. Smaller proportion of ester in fuel means smaller amount of built-in oxygen, making higher possibility of smoke formation. It is also observed from the tables that the lower injection pressure produced higher smoke. Lower injection pressure results in bigger droplets and hence bigger core. From earlier studies [19], it is found that the soot concentration is highest in the core region. Hence, bigger droplet means bigger core region and hence higher peak soot concentration. At an injection pressure of 220 bar, it is suspected that the fuel droplets are not only smaller in size, but also farther away from the nozzle. These two aspects combine together to produce lower soot concentration. The eventual smoke emission depends on oxidation of soot during combustion and later in the expansion stroke. While the former can be slightly different for ester–diesel blends due to built-in oxygen, the latter will be same for both diesel operation and ester based operation. Overall, it is found that for both ester–diesel blend types, the smoke has a decreasing trend with increasing ester proportion. Additionally, on an average, the smoke emission for pongemia ester–diesel blend is higher and exhaust temperature is lower than sunflower ester–diesel blend. This is probably due to higher oxidation of soot or after-burning during expansion stroke, causing increase in exhaust temperature, as these phenomenons generate additional heat. It is also observed that while blends of sunflower ester–diesel generally have lower exhaust temperature (0.4–3%) than diesel, the pongamia blends have higher values (0.5–7%). It appears that, generally, when smoke emission is lower, the exhaust temperature is higher or vice versa. This could be an indication of better soot oxidation resulting in higher gas temperature and lower smoke emission. For part load operation, the exhaust temperatures are lower compared to that of diesel for various types of blends and proportions of ester, the trend remaining steady for both. However, smoke level seems to be having slightly increasing trend with decreasing proportion of ester, with values for pongamia ester blends slightly higher than that of sunflower ester blends, especially at lower ester proportions.

5.2. Experiments with water–ester emulsion

The engine performance and emission characteristics using W/E emulsion have been investigated in this experimental study. Emulsification was achieved by the use of hydrophilic Tween 80 with HLB = 15 to attain emulsification stability. Water content of 2.5%, 5%, 7.5% and 10%, and homogenizing machine speed of 300 rpm were used to produce W/E emulsion. The methyl ester chosen for study are the sunflower oil ester and pongamia oil ester.

5.2.1. Effect of W/E emulsion on pressure–time histories

The comparison of cylinder pressure histories given in Fig. 6, obtained for neat vegetable oil ester and W/E emulsion, shows that the two graphs deviate near 359° CA. The W/E emulsion curve flattens for sometime on account of heat sink effect, and subsequently the speculated micro-explosion as mentioned in Ref. [20] occurs. The curve climbs steeply again, probably due to the multiple burn-
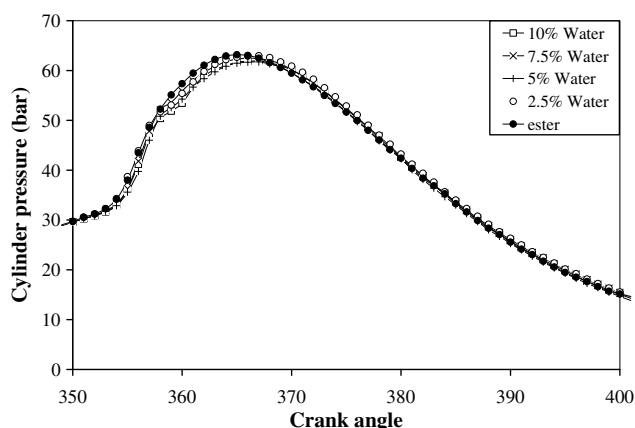
Fig. 6. Pressure–time histories for W/E emulsion for various water proportions at 23° bTDC injection timing and full load.

ing. The net effect of use of emulsion as compared to operation with neat vegetable oil is to shift the occurrence of peak pressure to the right (1–1.5°) and marginally increase its value (approx. 3%). A comparison of fuel consumed during W/E emulsion experiments indicated that the volume of fuel consumed was 122.6%, 123% and 132% more for full load than no load for 250, 220 and 190 bar respectively. Hence micro-explosions are more pronounced for full load due to bigger fuel droplets containing more water. At injection pressure of 250 bar, the fuel injected is just 5% more than that of the 190 bar at full load. The higher injection pressure results in smaller fuel droplets leading to smaller water droplets, which do not cause significant micro-explosion.

5.2.2. Effect of injection timing on pressure–time histories

The cylinder pressure histories for various injection timings are presented in Fig. 7. For 27.5° bTDC, the peak pressure occurs earlier than other injection timings and, therefore, has the highest value. For a smallest injection timing of 21.5° bTDC, the peak pressure occurs later by 3–4° CA leading to lower peak pressure. For the given engine, the ideal injection timing based on experiments with diesel fuel was found to be 367° crank angle (CA). Hence an injection timing of 24.5° bTDC seems appropriate when working with emulsion.

5.2.3. Effect of water proportion on pressure–time histories

A comparison of cylinder pressure histories for various water proportions in W/E emulsion indicated that the flattening of pressure curve during micro-explosion is more for 10% water content
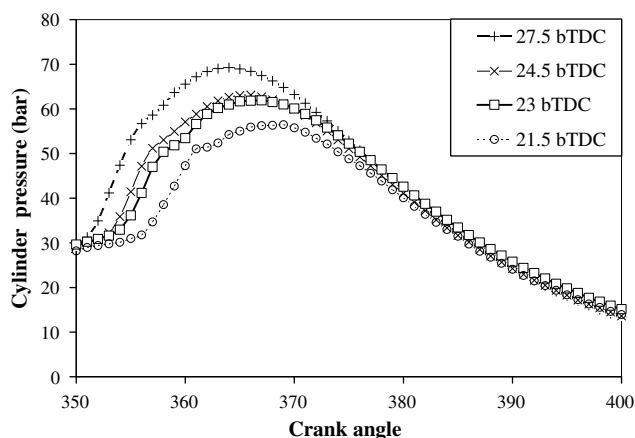

Fig. 7. Pressure–time histories for W/E emulsion for various injection timings at full load and 10% water.

than any other water proportions. This leads to pressure curve developing far too deeper into expansion stroke causing lower peak pressure. The 2.5% W/E emulsion has the highest peak pressure followed by 5%, 7.5% and 10% for all injection timings.

5.2.4. NOX and smoke emission for W/E emulsion

Many aspects like the nitrogen bearing fuel, excess oxygen, excessively high burning gas temperature, excessive time in the reaction zone etc., originated the formation of NO_X. Nitric oxide (NO) is the primary nitrogen oxide produced in engines. It originates primarily from atmospheric nitrogen oxidation based on the Zeldovich thermal NO mechanism [11]. The NO_X is expected to increase with load increment, because the increased load reduced the ignition delay and increased the peak gas pressure, temperature and fuel consumption rate. The reduction in NO_X emission is possible, therefore, by reducing the availability of oxygen or lowering peak pressure. The use of W/E emulsion can cause the reduction. When adding different amounts of water to the fuel, the corresponding amount of fuel is replaced with water leading to lower combustion temperature. Lower combustion temperature, however, directly influenced thermal NO formation due to reduction in chemical reaction rates for Zeldovich mechanism reactions as numerically established in Ref. [21].

The use of water in ester in emulsion formation brings down the temperature during evaporation at the intermediate stage of combustion much before peak pressure is reached. Based on the Zeldovich mechanism, the NO_X formation rate is expected to fall. However, subsequent spread of fuel particles due to micro-explosion might cause sudden spurt in temperature, and depending on various other conditions like size of particles, availability of air–oxygen, injection timing, and injection pressure, and therefore, initial size of the particles, leads to either increase or decrease in NO_X formation. As some conditions are stochastic in nature definite conclusions regarding NO_X formation cannot be arrived at and hence, certain NO_X results might appear contradictory.

Emulsion experiments have been taken up in this study mainly to quantify NO_X reduction in comparison with diesel operation. The results do indicate beneficial effects at certain mode of operation. However, because of the complexity involved in the combustion, while working with emulsion, some results indicate increase in NO_X contrary to general belief. The relative values of NO_X at various modes of operations of emulsion are presented in Tables 7 and 8. They are drawn for water-in-ester experiments for best BSEC for various injection pressures and water proportions in the emulsion. From these the following observations are made: for sunflower ester the better NO_X results occur at an injection pressure of 190 bar. At this pressure, the W/E emulsion brings down the NO_X emission by 44–48% compared to the neat ester for 5% and 7.5% water proportions. But no benefit is said to have been seen at very low (2.5%) or very high (10%) proportions. Explanation that can partially shed light on this aspect is as follows: for lower water proportion (2.5%) there is relatively less bending in pressure-history on account of micro-explosion. Hence, NO_X formation rate increases continuously. As for 10% water proportion, even though its formation rate appears to be reducing initially during micro explosion, because of wider distribution of fuel particles, higher availability of oxygen, and better environment for combustion, NO_X formation rate might have increased tremendously causing increase in NO_X emission. The injection timing associated with these results is found to be 23° bTDC. However, for injection timing of 23° and 24° bTDC, even though there is slight difference in pressure histories as seen in Fig. 7, the NO_X values could be found the same in some cases due to uncertainty in magnitude of temperature depression, splitting and spreading of fuel particles, formation rate, and availability of excess oxygen. Therefore, while 23° bTDC and 190 bar is an ideal operating point, even 24.5° bTDC could, some times, give similar

Table 7
Comparison of relative performance for water-in-sunflower ester emulsion for various water proportions and injection pressures

	Best inj. timing		BSEC		NO$_X$		Smoke		Exhaust temp.	
	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load
Diesel/190	24.5	24.5	1 (11905 kJ/kWh)	1 (10688 kJ/kWh)	1 (530 ppm)	1 (735 ppm)	1 (16 HSN)	1 (49 HSN)	1 (355 °C)	1 (545 °C)
W/SE/2.5/190	23.0	23.0	1.170	1.068	1.087	1.420	1.80	1.144	0.96	1.020
W/SE/2.5/220	24.5	23.0	1.220	1.116	0.863	1.075	1.56	0.797	0.93	0.970
W/SE/2.5/250	23.0	23.0	1.199	1.099	0.632	1.079	1.63	0.480	0.90	0.950
W/SE/5.0/190	23.0	23.0	1.231	1.112	0.868	0.875	1.90	1.271	0.97	1.030
W/SE/5.0/220	23.0	23.0	1.169	1.076	0.928	1.192	2.73	0.797	0.93	0.950
W/SE/5.0/250	23.0	23.0	1.162	1.064	0.723	1.275	1.48	0.995	0.90	0.940
W/SE/7.5/190	24.5	23.0	1.224	1.150	0.926	0.826	1.80	1.142	0.96	1.040
W/SE/7.5/220	24.5	23.0	1.174	1.106	0.901	1.213	1.57	0.864	0.92	0.976
W/SE/7.5/250	23.0	23.0	1.214	1.144	0.524	1.241	1.78	1.269	0.90	0.960
W/SE/10/190	24.5	24.5	1.282	1.119	1.205	1.373	1.98	1.349	0.98	1.034
W/SE/10/220	24.5	24.5	1.246	1.084	0.889	1.067	2.74	1.075	0.94	0.960
W/SE/10/250	23.0	24.5	1.308	1.106	0.550	1.420	2.50	1.051	0.91	0.940

Table 8
Comparison of relative performance for water-in-pongamia ester emulsion for various injection pressures

	Best inj. timing		BSEC		NO$_X$		Smoke		Exhaust temp.	
	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load
Diesel/190	24.5	24.5	1 (11905 kJ/kWh)	1 (10688 kJ/kWh)	1 (530 ppm)	1 (735 ppm)	1 (16 HSN)	1 (49 HSN)	1 (355 °C)	1 (545 °C)
W/PE/2.5/190	23.0	23.0	1.189	1.081	0.987	0.719	2.643	0.810	0.967	1.027
W/PE/2.5/220	23.0	23.0	1.184	1.112	0.768	0.570	2.119	0.520	0.942	0.991
W/PE/2.5/250	23.0	23.0	1.173	1.118	0.632	0.441	2.388	0.398	0.919	0.960
W/PE/5.0/190	23.0	23.0	1.264	1.160	0.492	0.661	1.988	0.369	0.950	1.020
W/PE/5.0/220	24.5	23.0	1.130	1.099	0.271	0.290	1.250	0.350	1.005	0.990
W/PE/5.0/250	24.5	23.0	1.160	1.137	0.610	0.310	1.586	0.500	0.900	0 .94
W/PE/7.5/190	24.5	23.0	1.224	1.147	0.819	0.423	2.862	0.611	0.960	1.028
W/PE/7.5/220	24.5	23.0	1.174	1.102	0.760	0.486	2.200	0.492	0.975	0.973
W/PE/7.5/250	24.5	24.5	1.214	1.137	0.660	0.575	2.618	0.698	0.907	0.957
W/PE/10/190	24.5	24.5	1.220	1.130	0.451	0.502	2.306	0.641	0.900	0.994
W/PE/10/220	24.5	24.5	1.240	1.099	0.244	0.291	1.338	0.410	1.020	1.064
W/PE/10/250	24.5	24.5	1.200	1.108	0.395	0.258	2.775	0.740	0.910	1.010

results. The part load operation has produced similar results, however with lower drop in NO$_X$ (20–26% in comparison with ester operation). This smaller drop is due to smaller temperature levels existing during part load operation. An injection pressure of 190 bar is found to be ideal, probably due to very high peak pressure levels and resulting higher system temperature. Hence the process of quenching and effect of quenching is more pronounced than at any other injection pressures where peak pressures are lower.

The reduction in NO$_X$ seems to have come at the cost of increase in smoke levels, more so for part load operation and many variants of sunflower ester. A theoretical analysis of dependence of NO$_X$ formation on OH radical, which is produced if water vapour is present, is discussed in Ref. [21]. The OH thus produced aids in the oxidation of soot thus reducing smoke emission. In this study, for pongamia based emulsion, at higher water proportions, the NO$_X$ is relatively lower probably on account of consumption of O for the production of OH radical as discussed in the above reference. However, this has not resulted in reduction in smoke values.

On the whole, there seems to be slight upward trend in smoke emission with increasing water content for both design and off-design operations, with sunflower ester-emulsion having higher values, especially at full load. However, as for exhaust temperature there is a steady trend for both full and part loads with nothing separating the two in their values. The increase in injection pressure seems to have caused reduction in exhaust temperature and an increase in smoke level. Lower exhaust temperatures indicate that the opportunity was not provided for the soot to undergo oxidation later in the exhaust stroke. Additionally there is a chance of water that was added undergoing condensation and getting absorbed by the particulates. On account of this also, the carbon particulates fail to undergo oxidation.

5.2.5. Comparison of BSEC for emulsion and blends

The brake specific energy consumption is higher for emulsion compared to the blends for sunflower ester. However, it is higher than the base line diesel for both blends and emulsions. Best results are associated with an injection pressure of 220 bar for blends of 10%, 20% and 40% blend (coming within 0.2–0.5%). Specific results also indicate that the BSEC increases with water initially and then decreases marginally for 10% water content, with lowest occurring at 2.5%. This value, however, is higher than that of any blends. Even in here, the trend shows that, injection pressure of 220 bar has lower BSEC values compared to any other pressures, the best injection timing for the blends and emulsions with lower water proportions being the value of 23° bTDC. For pongamia ester related experiments, even though trends appear to be same as that of sunflower ester, the efficiency is found to be lowest. However, since emission control is equally important, pongamia ester variants cannot be written off solely based on their efficiency.

5.3. Overall comparison

It is seen in Tables 5–8 that for the entire range of injection pressures and timings, the blends and emulsions do have BSEC at a higher level compared to sunflower ester (7–15% higher than baseline). The minimum for the whole range appears to be occurring at 5–20% blend. At part load, the BSEC for pongamia takes a plunge for the worse with 13–25% higher BSEC compared to baseline and for the entire range it is 9–25% higher. Here, too, a minimum for the emulsion appears to be occurring at lower water proportion (2.5%), and is increasing with it. For the injection pressure of 220 bar, it appears to be on the lower side, and pressure of 190 bar yielding higher values of BSEC. For the range, the best possible BSEC is associated with blend of 5–10%. Looking at the injection timing, for higher blend proportions, the best injection timing is said to be occurring at 23° bTDC where as, at lower blends and higher water proportions,

24.5° bTDC is found to be the best injection timing. As for smoke emission, at full load, for all water proportions, the emission is lower than that of the diesel fuel enabling a 10–60% reduction with emulsion. The trend indicates that the injection pressure of 190 bar produced highest smoke levels for all water proportions and increased with water contents. The trend also indicated that 250 and 220 bar produced smoke of lesser magnitude, compared to that of the 190 bar. However, in both the cases, it appeared to be decreasing first with water content and then increasing, to reach a maximum value at 10% water content. This increase is attributed to the lower temperature resulting from increased quenching effect beyond certain level of water proportion. The lower emission for injection pressures of 250 and 220 bar in comparison to 190 bar could also be explained in similar lines. A broader comparison indicated decrease in smoke level for emulsion compared to that of the blends. As regards BSEC for emulsion mode, it is lower for 220 bar compared to the other two injection pressures, seemingly agreeing with the result arrived at in the previous paragraph. Besides, the higher level of smoke associated with emulsions for all pressures seemed to be corresponding with the higher BSEC when compared to that of blends. Pongamia ester showed similar behaviour with respect to smoke emission. However, general level of smoke production is lower (20–65% less than diesel) than that of the sunflower. Again, for 220 bar, the smoke seemed to be decreasing with increasing water content, and increasing with water proportion for other injection pressures. In addition, emulsions produced more smoke at 190 and 250 bar compared to blends.

The nature of smoke emission at part load brings out an interesting picture. The emulsion at all pressures and all water proportions produce higher smoke levels (50–150%) compared to base line diesel operation showing increasing trend with water proportion. On the other hand, for blends it is lower than diesel in most of the cases. No clear distinction is seen in deciding appropriate injection pressure at part load. Similar trend is seen with the pongamia ester emulsion. However, 220 bar happens to be better at lowering the smoke level than other injection pressures.

The exhaust temperatures associated with the emulsion showed lower values compared to blends, lower than baseline for pressures of 220 and 250 bar. Surprisingly, for 190 bar, the trend not only showed an increased exhaust temperature, but also it is increasing with water content. There is no surprise in exhaust temperature being smaller and smaller for successive higher injection pressures as proved by the pressure histories seen in Fig. 8. The exhaust gas temperature of W/PE shows a similar trend. Here again, the temperature for emulsions are lower than blends. The temperature for 250 bar is lower than 220 and 190 bar. The best injection timing for W/PE is found to be 23° bTDC for most of the blend proportions as against 24.5° bTDC for W/SE. Based on visual observation of the pressure histories, it is noticed that the depression caused by the micro explosion is less pronounced. Hence, slightly retarded (23° bTDC) timing is found to be optimal. However, for 190 bar and 10% water proportion, the "depression" is quite substantial and peak appeared to have shifted to the right than any of the other curves. Moreover, for the above combination, the best injection timing is found to be 24.5° bTDC. No retardation required as the "depression" caused the peak to occur at the place where best performance is attained. Fig. 8 also indicates that the curve for 220 bar drops below all other curves soon after peaking, indicating that the energy utilisation is far more effective with a pressure of 220 bar, which is further proved by the fact that the exhaust temperature is the lowest for a pressure of 220 bar. The temperature, for all the injection pressures, is lower than that of diesel. For emulsion, the temperature is lower for 190 and 250 bar compared to their blends. However, for a pressure of 220 bar no variation is seen. In general, there are many reasons for lower exhaust temperature; the early occurrence of peak pressure, lower peak
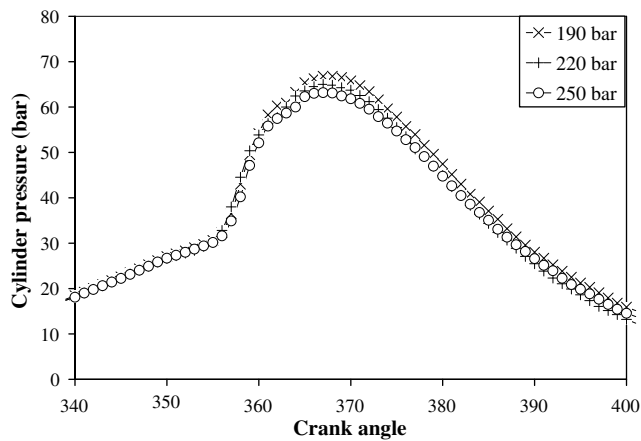
Fig. 8. Pressure–time histories for three different injection pressures with 10% water proportion for W/PE emulsion at full load.

pressure, the peak pressure occurring at the appropriate location and good utilisation of energy during expansion, absence of afterburn etc., being some. At part load operation, the "pressure depression" is absent; therefore, it behaves like neat ester. Hence, slightly retarded injection timing found to be appropriate, like with neat esters. For pongamia emulsion, at 220 bar the exhaust temperature is said to have risen, while for 190 and 250 bar it is lowered, compared to blends, with the lowest occurring at a pressure of 250 bar. However, it is observed that almost all temperature values are lower than those found in diesel fuel operation.

5.4. Determination of best operating condition for 24 fuel variants and the best fuel variant

Complete details of performance and emission parameters for all the 24 fuel variants for the best BSEC are shown in Table 9. An overall comparison indicates that the BSEC varied from 0.2% to 10% for full load and 2–24% for part load, when compared to diesel operation, with the best values associated with SE/D (sunflower

ester–diesel) blends of B10, B20 and B40, at full and part loads. The injection pressures associated with these results are 220 and 250 bar, respectively, and the associated injection timing being 23° bTDC. However, for lower ester blends, the best injection timing is associated with 24.5° bTDC.

5.5. Comparison of cycle-by-cycle fluctuation

The c-b-c (cycle-by-cycle) fluctuation is known to be of smaller magnitude in diesel engine compared to SI engine. An attempt has been made here to see the effect of presence of ester in diesel and water in ester on c-b-c fluctuation. The peak pressure has been used as the combustion parameter for comparison. The mean and standard deviation for 100 cycles were calculated, and then coefficient of variation (COV) was determined. For most of the full load operations of the blends of esters, the COV (p_{max}) was found to be lesser than that of diesel operation (1.55%), and modes which had higher than the above value were associated with extreme injection timings of 21.5° and 27.5° bTDC. The higher COV (1.546–6%) are associated with lower blends and injection pressure of 250 bar. For injection pressures of 250 and 220 bar, for all blends taken together, the COV is higher (0.876–4.358% and 1.27–2.47%, respectively) than that of 190 bar (0.524–2.50%). Generally, for part load operation, the COV is higher (0.88–4.96). Elimination of c-b-c fluctuation reduces the instability in the combustion process. Therefore, operation needs to be carried out at an operating point where COV is minimal. A combination of full load, higher blend, 190 bar-injection-pressure, and 24.5° bTDC would provide an ideal operating point for blend fuel variants. For emulsions, the COV varies from 0.68–3.39% for all fuel variants and modes of operation. Generally, the lower COVs are associated with lower water proportions (most 2.5% and a few 5%) and injection timings of 23° and 24.5° bTDC. A one off experiment with 20% water proportion yielded a very high (COV = 3.8%) c-b-c fluctuation along with very high (HSN = 73%) amount of smoke. However, the COV (p_{max}) of any fuel variant in any mode of operation is considerably lesser than that of SI engine (8–12% [22]). For part load operations, COV (p_{max}) is higher than full load operation, more so for higher proportion of water in the emulsion.

Table 9
Comparison of 24 fuel variants at best performance level for design and off-design conditions relative to diesel operation

Sl. no.	Fuel variant	Best values for max. brake specific energy consumption									
		BSEC		NO$_X$		Smoke		Injection pressure		Injection timing	
		Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load	Full load	Part load
1.	S.ester	1.048	1.077	0.820	0.667	0.661	0.971	220	220	23.0	24.5
2.	S/D/80	1.016	1.047	0.910	0.543	0.614	1.000	220	250	23.0	23.0
3.	S/D/60	1.011	1.062	0.870	0.623	0.671	0.780	220	250	23.0	23.0
4.	S/D/40	1.002	1.019	1.540	0.726	0.373	0.680	190	250	23.0	23.0
5.	S/D/20	1.005	1.023	0.904	0.726	0.681	0.721	220	250	24.5	23.0
6.	S/D/10	1.004	1.045	0.902	0.590	0.763	0.622	220	250	24.5	23.0
7.	S/D/5	1.021	1.079	0.921	0.923	0.679	0.971	220	220	24.5	23.0
8.	S/D/2	1.031	1.077	1.404	0.720	0.644	0.914	190	250	23.0	23.0
9.	P.ester	1.088	1.171	1.500	1.392	0.502	1.193	220	190	23.0	23.0
10.	P/D/80	1.094	1.088	0.670	1.374	0.636	0.607	220	190	23.0	23.0
11.	P/D/60	1.099	1.110	1.540	1.254	0.527	0.710	190	190	23.0	23.0
12.	P/D/40	1.100	1.132	0.713	0.651	0.636	0.842	220	250	23.0	23.0
13.	P/D/20	1.091	1.139	0.660	0.620	0.814	0.762	220	250	23.0	23.0
14.	P/D/10	1.067	1.135	1.020	1.118	0.415	0.835	190	190	24.5	23.0
15.	P/D/5	1.081	1.121	0.904	0.578	0.576	0.572	190	250	24.5	24.5
16.	P/D/2	1.069	1.108	0.793	0.569	0.592	0.565	190	250	24.5	23.0
17.	W/SE/2.5	1.068	1.170	1.420	1.087	1.440	1.800	190	190	23.0	23.0
18.	W/SE/5.0	1.064	1.162	1.275	0.723	0.995	1.480	250	250	23.0	23.0
19.	W/SE/7.5	1.106	1.174	1.213	0.901	0.864	1.570	220	220	23.0	24.5
20.	W/SE/10	1.084	1.246	1.067	0.889	1.075	2.740	220	220	24.5	24.5
21.	W/PE/2.5	1.081	1.172	0.719	0.632	0.810	2.390	190	250	23.0	23.0
22.	W/PE/5.0	1.099	1.130	0.290	0.271	0.350	1.250	220	220	23.0	24.5
23.	W/PE/7.5	1.102	1.174	0.486	0.760	0.492	2.200	220	220	23.0	24.5
24.	W/PE /10	1.099	1.200	0.291	0.395	0.410	2.780	220	250	24.5	24.5

6. Conclusions

The experiments conducted show that for all fuel variants considered in this study, the BSEC is higher than that of diesel. Improvement in emission characteristics is possible with various fuel variants with a certain increase in BSEC compared to diesel. While use of water emulsion brings down NO_X enormously, various ester–diesel blends can do so at higher injection pressure or retarded injection timing. Reduction in smoke is also possible with emulsion and blends at certain operating modes. The recommended operating point for various objectives is indicated below:

1. If the sole objective is better efficiency, then sunflower ester–diesel blend with 10–40% ester should be considered at all loads, with a resulting higher BSEC of 0.2–0.5% and 1.9–5% at full load and part load, respectively. The associated injection pressure is 220 bar for full load and 250 bar for part load respectively and injection timing is 23° bTDC for both.
2. If the objective is to reduce NO_X emission, 71% reduction in NO_X is possible at full load with 5% water-in-pongamia ester emulsion, with 10% rise in BSEC for an injection pressure of 220 bar and a timing of 23° bTDC. For part load operation, 75% reduction in NO_X was observed for 10% water-in-pongamia ester emulsion at an injection pressure of 220 bar and a timing of 24.5° bTDC, accompanied by 24% increase in BSEC.
3. If the objective is to reduce smoke emission, the use of 5% water-in-pongamia at an injection pressure of 220 bar, and a timing of 23° bTDC, would result in 65% reduction and 10% increase in BSEC at full load. For part load, 2% pongamia ester–diesel blend, an injection pressure of 250 bar and a timing of 23° bTDC produced 43% reduction in smoke and 11% increase in BSEC.

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