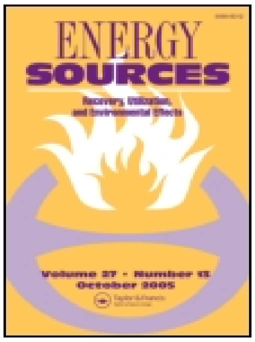

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An Analysis of Cycle-by-cycle Fluctuation in Combustion Parameter in CI Engine Operation for Various Bio-fuels

S. BEKAL[1] and T. P. ASHOK BABU[1]

[1]Department of Mechanical Engineering, National Institute of Technology, Karnataka, Suratkal, India

Abstract *The cycle-by-cycle fluctuations in peak pressure of combustion in a CI engine were studied for lower and higher blends of diesel and ester, and water-in-ester emulsions, at four injection timings and three injection pressures using coefficient of variation. The sunflower ester-diesel blends are found to have lower cycle-by-cycle fluctuations than pongemia ester-diesel blends. The fluctuations are found to be higher than that of diesel for higher blend proportions of ester. The water-in-ester emulsion show higher cycle-by-cycle fluctuations than that of ester-diesel blends. In most cases, the Brake specific energy consumption is also found to be higher where the coefficient of variation has higher values.*

Keywords cycle-by-cycle fluctuation, ester-diesel blend, injection pressure, peak pressure, water-in-ester emulsion

1. Introduction

The cycle-by-cycle (C-b-C) fluctuation in various combustion parameters in SI engine is well documented in Heywood (1988). Some of the factors that are responsible for C-b-C fluctuation in SI engine, such as variation in gas motion in the cylinder during combustion, cycle-by-cycle, and variations in mixture composition within the cylinder each cycle, are also present in diesel engines producing C-b-C fluctuation in it (Longwic et al., 2009).

Litak et al. (2003) have shown in their work on analysis of C-b-C fluctuation on engine modeling that small amplitude of these fluctuations affects considerably the stability of a combustion process. Earlier, Roberts et al. (1997) laid the reason on stochastic disturbances and Daw et al. (1996) on nonlinear dynamics of combustion process.

Litak et al. (2009a) analyzed cycle-to-cycle fluctuation in peak pressure and peak pressure angle at different spark advance angles for an SI engine, and found that there was significant difference in fluctuation depending on the spark advance angle.

While peak pressure and rate of pressure rise are generally used for the study of fluctuations, Litak et al. (2009b) when working with natural gas as fuel used, indicated mean effective pressure for the study of oscillations.

Address correspondence to Sudesh Bekal, Department of Mechanical Engineering, NMAM Institute of Technology, Nitte 574110 India. E-mail: sudeshbekal@rediffmail.com

Vegetable oil (Alton et al., 2000), esters of inedible vegetable oil (Usta, 2005; Azam et al., 2005), ethanol, and ether-based fuels are some of the options available for replacement of diesel in the CI engine. The water emulsions can be used in diesel engines for improving efficiency and reducing pollution (Abu-Zaid, 2004). The authors, in their work on water-in-ester emulsion (Bekal and Ashok Babu, 2008), studied the pollution and performance aspects. The stochastic nature of fuel distribution, mixture formation, and fuel atomization associated with micro-explosion and micro-droplet distribution are expected to cause higher C-b-C fluctuations while working with water-ester emulsion. Hence, C-b-C fluctuation in the CI engine run on alternative fuel variants needs to be recorded and studied to shed light on such operations.

In this work, the C-b-C fluctuations are determined for diesel engine combustion while working with various fuel variants derived from pongamia ester and sunflower ester. While using peak pressure of combustion as the parameter for comparing C-b-C fluctuation, the data have been developed for several operational modes, such as four injection timings and three injection pressures. Using the results obtained from the experimentation, the brake specific energy consumption (BSEC) and C-b-C fluctuations are determined, and relationship is established.

2. Materials and Methods

The methyl ester was prepared from sunflower and pongamia oil using a single stage alkali method. Initially, potassium methoxide was prepared by dissolving 6 gm of KOH in 250 ml of methanol. The rest of the procedure involved heating the oil-methoxide mixture at 60°C in a reflux condenser using a heating mantle for 2 h. Subsequently, the ester was separated from glycerol and washed with water several times until neutral pH value was obtained; thereupon, the ester was heated until traces of water settled at the bottom of the flask.

3. Methodology

3.1. *Engine Set-up*

The engine experimentation was performed on a single cylinder, four-stroke, water-cooled compression ignition engine, whose technical specifications along with specification of accessory parts are given in Table 1. The schematic diagram of the engine test rig is presented in Figure 1. The engine is fitted with two pressure sensors (PCB, Depew, NY) for the measurement of cylinder gas pressure and injection line pressure. The sensors are connected to charge amplifiers using low noise cables, and then interfaced with a computer using an analog-to-digital converter (ADC) card. There are five temperature sensors—thermocouple based (K-type-Chromel-alumel)—for the measurement of exhaust gas temperature, cooling water temperature, and atmospheric temperature. A dedicated software stores gas pressure for all the 720 degrees of a cycle for 100 cycles.

3.2. *Engine Experimentation*

The experiments were conducted on the CI engine using fuel variants obtained from two types of methyl esters, namely, sunflower ester and pongamia ester. The fuels used were ester-diesel blends with B2, B5, B10, B20, B40, B60, and B80 ester proportions and water-in-ester emulsion with W2.5, W5, W7.5, and W10 water proportions. For each of

Table 1
Specification of the test engine and accessories

Engine specification		Specification of engine accessories	
Description of the engine	Single cylinder, constant speed, water cooled, stationary, vertical C.I engine	Fuel injector	Single multi-jet injector Mico 9430031258E LIC Bosch 791
Rated speed	1,500 rpm		Nozzle dia.: 9.2 mm
Compression ratio	17.5:1		Length of the nozzle: 17 mm
Normal injection pressure	190 bar		Angle of injector: 15 degree with axis of piston motion (vertical)
Rated power	7 hp		
Cylinder bore	87.5 mm		
Stroke	110 mm	Injection pump type	Jerk-pump with rack and pinion
Clearance volume	41.09 mm^3	Combustion chamber	Hemispherical bowl in piston-52 mm dia.
Total swept volume	661 mm^3	Dynamometer type	Eddy current
Normal injection timing	24.5° bTDC	Pressure sensor	Peizo electric
		Exhaust temperature measurement	Thermocouple (Chromel Alumel-k type)
		Valve timing:	
		Inlet valve open	:10 degrees before TDC
		Inlet valve close	:38.74 degrees after BDC
		Exhaust valve open	:31 degrees before BDC
		Exhaust valve close	:12 degrees after TDC

these fuel combinations, the experiments were performed at 21.5, 23, 24.5, and 27.5° bTDC injection timings. Further, at each injection timing the experiments were carried out with three injection pressures—190, 220, and 250 bar. The analysis was performed for 50% and full load. The number of experiments conducted add up to a grand total of 264. Before starting the experiment with a new fuel variant, fuel from 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 Tween80 emulsifier in methyl ester produced from vegetable oil, and then adding distilled water to it while being stirred.

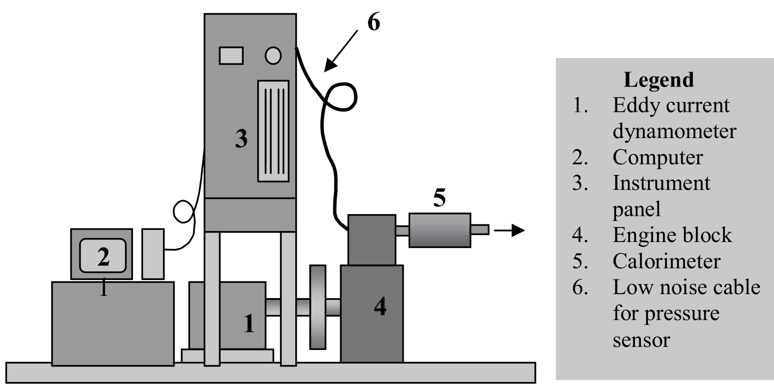

Figure 1. Engine unit and accessories.

3.3. Statistical Procedure

A statistical parameter "coefficient of variation" (COV) was used for statistical analysis of fluctuation in peak pressure of engine combustion. The COV is calculated using Eq. (1) given below:

$$\text{Coefficient of variation (COV)} = \text{Standard deviation} \div \text{mean of peak pressure} \quad (1)$$

The parameters required for the calculation—standard deviation and mean—were determined using an excel spread sheet; the 720 pressure data for each cycle was transferred to the spreadsheet for 100 cycles and then the parameters were calculated using a built in function, extending it subsequently to all 720 data. The coefficient of variation was then determined by dividing standard deviation by mean value for all the 720 degrees of crank angle after which the COV of the peak pressure was determined.

4. Results and Discussion

The authors in their earlier research publication (Bekal and Ashok Babu, 2008) focused on emission characteristics and performance. In this article, the focus is on the C-b-C fluctuation and performance.

4.1. C-b-C Fluctuation in Peak Pressure for Ester-diesel Blend

The values of coefficient of variation for fluctuation in peak pressure are lower for 23 and 24.5° bTDC as seen in Figure 2, which is drawn for ester-diesel blend. A similar trend is observed with data for other fuel combinations, including water-in-ester emulsion variants and all injection pressure modes. Hence, in this study, a comparison is made of the COVs for various fuel variants only at injection timings of 23 and 24.5° bTDC. The values of

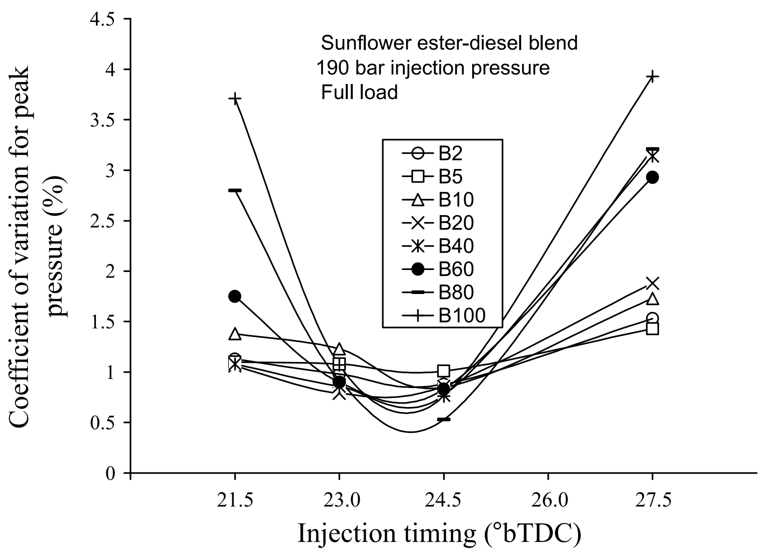

Figure 2. Coefficient of variation for fluctuation in peak pressure for sunflower ester-diesel blends at various injection timing.

COV at these injection timings are listed in Table 2 for all fuel variants derived from pongamia and sunflower ester. It is seen in the table that for all injection pressures, COV is higher for part load in comparison with full load; and that for an injection pressure of 220 bar, the COV is more than other injection pressures for most of the blends at both full and part loads. The trend shows an increase in COV with an increase in ester proportion in the blend except at B20 and an injection timing of 23° bTDC having COV marginally better than that of 24.5° bTDC. The COVs for sunflower ester-diesel blends at part load are much higher than that of pongamia ester-diesel blends at both 23 and 24.5° bTDC; and, excepting 190 bar pressure, the COVs are higher than pongamia ester-diesel blends. At lower blends, the mixture behaves more like diesel operation; and, hence, retarded injection timing of 23° bTDC is to be interpreted as unstable operation. Similarly, at higher blends an injection timing of 24.5° bTDC was found to be unstable.

In this work, for comparing the performance of an engine, a parameter known as brake specific fuel consumption is employed because of use of multiple fuel variants, and is given by Eq. (2) shown below:

$$\begin{aligned}&\text{Brake specific energy consumption (BSEC)}\\&\quad = \text{total fuel consumption (kg/h)} \times \text{calorific value (kJ/kg)} \div \text{brake power (kW)}\end{aligned} \tag{2}$$

For the comparison of BSEC and C-b-C fluctuation at various blends and injection pressures, the relative BSEC for ester-diesel blends at 23 and 24.5° bTDC for pongamia and sunflower ester are presented in Table 3. For sunflower ester-diesel blends, it is found that the relative BSEC is lower for full load than that of part load for almost all blends—with few exceptions at lower blends—and for all injection pressures and both 23 and 24.5° bTDC injection timings; incidentally, Table 2 shows that COV is higher as well for part loads at all the operating conditions considered here—67% more than full for 190 bar, 24% more for 220 bar, and 85% more for 250 bar on comparing the average of COV over all the blends for each injection pressure. On comparing the relative BSEC at the two injection timings (23 and 24.5° bTDC), it is found that the values are lower for the latter injection timing and again, the COV values are also lower for the same injection timing—17% less than 23° bTDC for full load at 190 bar, 10% less at 220 bar, 9% more for 250 bar, insignificant difference at part load at 190 and 220 bar, and 12% more at 250 bar injection timing. This implies that injection pressure does not really affect the C-b-C fluctuation.

For pongamia ester-diesel blends, the BSEC is smaller for full load than the part load operation; however, the range is on the higher side compared to sunflower ester-diesel blends. The COVs for full load operation are smaller than part load indicating more instability with part load. On comparing the stability of operation, it is found that the instability is more with sunflower ester-diesel operations at 220 and 250 bar than the pongamia ester-diesel blends as indicated by higher COVs for sunflower ester-based fuel variants; but at 190 bar injection pressure, the sunflower ester-based fuel variants have better stability.

For pongamia ester-diesel blends, for both the injection timing of 23 and 24.5° bTDC, the BSEC is lower for full load than the part load at all blends, except at very low blends; the level of these BSEC values are higher than that for sunflower ester-diesel blends, and more for an injection timing of 23° bTDC. A comparison of COVs given in Table 2 indicated a similar variation, with part loads having higher COVs at all injection pressures; however, these COVs are smaller than that of sunflower ester-diesel blends. The difference in the COVs—calculated by averaging the COVs at each injection pressure

Table 2

Coefficient of variation (%) for fluctuation in peak pressure for ester-diesel blends and water-in-ester emulsion at full and part loads

Fuel variant	Inj. timing (°bTDC)	For sunflower ester based						For pongamia ester based					
		Full load			Part load			Full load			Part load		
		Injection pressure (bar)			Injection pressure (bar)			Injection pressure (bar)			Injection pressure (bar)		
		190	220	250	190	220	250	190	220	250	190	220	250
Ester-diesel blend													
B2	23	0.98	3.13	0.94	1.70	1.31	1.33	1.06	1.23	0.70	1.38	1.95	1.59
	24.5	0.88	2.48	1.03	2.03	2.68	1.84	1.00	1.25	0.84	1.47	2.60	2.05
B5	23	1.08	3.25	1.06	1.50	4.29	1.79	1.28	1.55	0.93	1.33	2.02	1.85
	24.5	1.01	2.88	1.12	1.62	4.07	1.81	1.11	1.33	1.04	1.40	2.71	2.16
B10	23	1.23	3.59	1.25	1.81	3.51	2.50	1.17	1.87	1.46	1.49	1.73	1.70
	24.5	0.85	3.47	1.17	1.94	3.27	3.05	1.35	1.74	1.18	1.51	2.06	1.08
B20	23	0.79	2.33	0.78	1.26	2.47	1.53	1.40	0.97	0.93	1.50	1.41	1.21
	24.5	0.86	1.88	0.91	1.14	2.34	1.70	1.41	0.74	1.05	1.73	1.72	1.34
B40	23	0.86	3.29	1.23	1.45	2.85	3.09	1.53	1.23	1.32	1.88	1.87	2.52
	24.5	0.77	3.10	1.22	1.16	2.91	3.24	1.54	1.53	1.34	1.62	2.45	2.69
B60	23	0.90	2.46	1.84	1.60	2.22	3.23	1.60	1.90	1.61	1.80	2.14	2.33
	24.5	0.83	2.15	2.11	1.25	2.57	3.60	1.67	1.75	1.90	2.05	2.32	2.78
B80	23	0.92	2.40	1.34	1.22	4.87	1.31	1.76	3.18	1.52	1.96	1.72	2.13
	24.5	0.53	2.18	1.53	1.43	4.41	1.94	1.85	3.76	1.74	2.17	2.17	2.73
Water-in-ester emulsion													
B100	23	1.07	2.76	1.32	1.31	5.2	3.05	1.41	1.47	0.96	2.03	1.56	1.80
	24.5	0.76	2.56	1.58	1.50	5.53	2.88	1.67	1.21	1.02	2.11	2.18	2.34
W2.5	23	0.836	0.95	5.51	1.15	2.2	5.74	1.68	0.99	3.67	2.28	2.47	2.43
	24.5	0.708	0.89	5.27	0.72	1.85	5.52	1.42	1.12	3.16	2.03	2.8	2.73
W5	23	0.946	0.865	1.76	1.55	1.56	4	1.55	1.51	1.67	2.51	2.11	3.13
	24.5	1.084	0.851	1.82	1.19	1.34	4.24	1.78	1.94	1.28	2.20	2.11	3.2
W7.5	23	1.1	0.699	1.34	2.24	1.34	5.58	1.14	0.78	2.66	2.85	2.68	3.35
	24.5	1.217	0.680	1.18	0.91	0.94	3.62	0.96	0.78	2.3	2.34	3.03	3.43
W10	23	1.225	0.99	2.89	1.49	1.57	5.04	1.79	1.42	3.17	3.06	2.86	3.74
	24.5	0.883	0.846	2.62	1.2	1.33	4.78	1.62	2.05	2.76	2.57	3.13	4.43

B10—ester-diesel blend with 10% ester by volume; W2.5—2.5% water proportion in the emulsion by volume.

Table 3

Difference in BSEC (in percentage) with respect to diesel (BSEC for diesel operation: Full load, 10,688 kJ/kWh; part load (50%), 11,905 kJ/kWh)

		For sunflower ester based						For pongamia ester based					
		Full load			Part load			Full load			Part load		
	Inj. timing	Injection pressure (bar)			Injection pressure (bar)			Injection pressure (bar)			Injection pressure (bar)		
Fuel variant	(°bTDC)	190	220	250	190	220	250	190	220	250	190	220	250
B2	23	0.842	9.122	5.071	6.115	9.618	4.829	4.042	10.310	2.077	13.567	11.466	8.274
	24.5	0.674	2.498	1.188	2.561	4.930	8.106	5.071	5.632	2.863	9.533	9.197	7.097
B5	23	0.346	8.112	5.071	9.954	10.046	7.518	4.903	10.853	2.077	18.210	13.818	11.969
	24.5	1.038	3.247	1.488	5.922	8.047	12.306	5.913	8.065	4.041	12.557	9.785	9.113
B10	23	0.30	8.711	5.539	11.718	8.820	6.678	5.286	10.713	2.806	16.354	14.691	11.969
	24.5	0.402	3.134	1.329	7.266	11.642	8.946	5.728	7.503	4.041	11.969	7.349	8.609
B20	23	0.552	9.085	5.239	5.510	8.064	6.089	5.829	9.1879	3.237	17.262	19.194	11.718
	24.5	0.487	3.162	0.805	4.158	16.422	10.36	7.382	5.913	4.229	11.843	8.945	6.845
B40	23	0.674	9.815	3.761	6.619	11.953	8.862	5.810	11.284	3.761	14.389	21.546	14.271
	24.5	−0.159	2.900	1.422	3.99	15.993	11.97	7.475	5.071	6.090	12.431	10.037	11.717
B60	23	0.299	9.282	2.732	14.742	11.718	15.077	4.771	8.973	2.919	18.891	23.226	21.629
	24.5	−0.2619	2.246	1.637	5.334	8.694	13.65	6.923	3.358	5.351	13.901	12.305	15.749
B80	23	1.198	9.431	2.33	9.828	10.785	15.876	6.016	10.722	8.711	18.858	23.141	22.360
	24.5	0.543	2.002	1.488	3.99	7.871	13.901	6.858	3.854	6.306	18.269	24.317	20.537
B100	23	1.656	10.05	3.228	16.665	9.744	18.941	7.036	11.985	8.533	20.958	28.769	24.007
	24.5	2.115	2.966	1.909	7.518	10.626	20.286	9.356	8.532	7.597	21.671	26.921	22.301
W2.5	23	5.735	10.497	8.813	17.018	24.409	25.661	11.059	3.854	6.474	18.857	11.549	21.545
	24.5	9.599	11.202	14.926	26.938	22.015	24.409	9.468	7.877	8.252	25.577	22.637	23.057
W5.0	23	10.160	6.605	5.389	23.141	16.892	16.169	14.867	9.122	7.877	26.409	21.486	34.817
	24.5	13.183	8.579	16.083	28.273	17.446	20.235	14.86	8.822	10.497	28.483	27.467	25.409
W7.5	23	13.931	9.496	13.270	34.733	22.847	21.385	15.082	11.807	11.246	38.765	27.593	44.729
	24.5	14.586	11.592	16.298	22.393	26.963	24.384	12.836	8.252	9.281	14.237	19.529	16.589
W10	23	15.159	17.309	9.431	31.625	24.611	30.760	16.111	14.867	13.585	38.983	33.926	49.525
	24.5	19.760	7.410	15.550	29.500	27.173	31.230	11.760	8.822	9.730	22.125	33.557	24.905

over the entire range of blends—on computation is found to be 20% more than the full load at 190 bar, 22% more for 220 bar, and 65% more at 250 bar; on comparing the COVs for the two injection timings, it was found that 24.5° bTDC has 18% higher COV at 190 bar and full load, 0.7% less at 220 bar and 7% more at 250 bar, and part load, COV is 4.7% more for 24.5° bTDC at 190 bar, 26% more at 220 bar, and 13% more at 250 bar. A comparison of BSEC for various injection pressures indicates that for full load at 23° bTDC, the values for 220 bar is well above those of 190 and 250 bar, and for part load the values for 220 and 250 bar are similar and higher. At 24.5° bTDC, all the values are almost the same at all injection pressures. The average COV agree in that, for 23° bTDC, it has a higher value at 220 bar (1.67) compared to values at other pressures (1.17, 1.4) for full load; and for part load, values of 220 and 250 bar are similar (1.8, 1.89), while 190 bar has a lower value for 24.5° bTDC; however, the BSEC and COV do not quite agree except for the fact that for part load the average values of COV are closer for 220 and 250 bar injection pressure.

The relative BSEC is more than zero for all cases, indicating that for all cases the performance is poorer than that of diesel operation; however, when it comes to COV values, there are many instances where the values are lower than diesel's.

4.2. C-b-C Fluctuation in Peak Pressure for Water-in-ester Emulsion

Even though higher proportion of water in water-in-ester emulsion reduced certain pollutants (Bekal and Ashok Babu, 2008) by virtue of lower temperature, it creates instability during combustion. Also, in a few cases, especially at low pressure of injection, it is so with 23° bTDC. However, at an injection pressure of 250 bar it happened with 24.5° bTDC. A similar trend is observed with ester prepared from pongamia.

For water-in-sunflower ester emulsion, it can be seen from Table 3 that the relative BSEC is lower for full load than that of part load for all water proportions, and for all injection pressures and for both 23 and 24.5° bTDC injection timings; coincidentally, Table 2 shows that the COV is higher as well for part loads at all the operating conditions considered here—31% more than full for 190 bar, 79% more for 220 bar, and 72% more for 250 bar on comparing the average of COV values over all the water proportions for each injection pressure. On comparing the relative BSEC at the two injection timings, 23 and 24.5° bTDC, it is found that the values are slightly higher for the latter injection timing, however, the COV values are lower for the same injection timing, 2% less than 23° bTDC for full load at 190 bar, 7.5% less at 220 bar, 5% less for 250 bar; the differences at part load are 37% less at 190 bar, 18% less at 220 bar, and 11% less at 250 bar injection pressure. However, the above differences are relatively small to be alarmed by the contradiction. A comparison of injection pressure indicates that even though there is not much of a difference in relative BSEC for various injection pressures, the operation with an injection pressure of 190 and 220 bar, did produce very small (0.88 to 1.66%) COV compared to that of 250 bar (2.8 to 5%); instability appears to be more at 220 bar injection pressure.

For water-in-pongamia ester emulsion, the BSEC is smaller for full load than the part load operation; however, the range is slightly on the lower side compared to that of water-in-sunflower ester emulsion, and it is negligible. It is found from Table 2 that the COVs for a full load operation is smaller than that of part load indicating more instability with part load, as observed with water-in-sunflower ester emulsion. Comparing the stability of operation of pongamia and sunflower ester-derived emulsions, the instability is more with pongamia ester emulsion than sunflower ester emulsion at lower injection pressures of 190 and 220 bar; but at 250 bar injection pressure, the pongamia ester emulsion fuel variants have better stability.

The work with water-in-ester emulsion has indicated flattening of the pressure-crank angle after the commencement of combustion; this has caused a shift in the occurrence of peak pressure. The reason for this behavior could be attributed to micro-explosion caused by vigorous vaporization of water present in the emulsion, soon after combustion began (Abu-Zaid, 2004). The magnitude and occurrence of this micro-explosion is stochastic in nature, and depends on several factors, such as distribution of the spray particles, the surrounding conditions, and the size of fuel spray; hence, no definite trend was observed in the "depression" in the pressure-crank angle histories. However, from the comparison of relative BSEC values shown in Table 3, it is seen that performance has not been benefited by the micro-explosions as the relatives values for all conditions, modes and variants, the value of relative BSECs are more than zero. However, it is found that the operation with 10% water proportion has produced marginally higher "depression" than that of other water proportions (Bekal and Ashok Babu 2008)—reduction in gas pressure due to flattening of the curve is 5.4% with W10 (water proportion 10%) compared to 3.7% with other water proportions in some of the cases. Table 3 also indicates higher relative BSEC at W10; thus, there is no benefit gained even with large water proportion and relatively bigger "flattening" caused due to micro-explosion; on the contrary it has increased the C-b-C fluctuations. The expectation that the introduction of water in emulsified form might improve the performance due to better mixing of air and fuel—due to micro-explosion—is not vindicated; however, the micro-explosion, while bring the local temperature down, may tear off the flame fronts, extinguishing it temporarily; and also cause the fuel droplets to be deposited onto the wall of the combustion chamber. It could also be speculated that the micro-explosion might have caused more after burning, contributing to poorer BSEC.

4.3. COV with Hyper-exponential Distribution

The COV values higher than 1 are considered to be in hyper-exponential distribution. The values of COV for ester-diesel blend shown in Table 2 indicate that, for most of the cases, the values lie in the hyper-exponential distribution. However, for sunflower ester-diesel blend, many COVs with value less than 1 are seen for full load and 190 bar injection pressure. As for water-in-ester emulsion, on examining Table 2, again, most of the entries are in the hyper exponential distribution. However, like with ester-diesel blends, for water-in-ester emulsion also lower COVs are observed with sunflower ester-related emulsion; again, mostly for an injection pressure of 190 bar and a few at 220 bar.

5. Conclusions

Based on the study and discussion carried out in the previous section, the following conclusions can be drawn:

- The COV for fluctuation in peak pressure is found to be higher for part load for both ester-diesel blends and water-in-ester emulsions. The associated relative BSEC is also higher corresponding to higher COV in most of the cases.
- For blends, the COVs are higher for higher ester proportions in the blend for both part and full load operations, with sunflower-diesel blends showing higher COVs compared to pongamia-diesel blends.

- Water-in-ester emulsion produced higher COVs than blends. Lower COVs are observed with injection timings of 23 and 24.5° bTDC.
- The relative BSEC is more than zero for all operating conditions-indicating that none of the fuel combinations are better than diesel; however, the blends of sunflower ester and diesel come close to diesel's performance at both 23 and 24.5° bTDC. The micro-explosion believed to be occurring when water-in-ester emulsion was used, did not improve the performance.
- Almost all the COV values are in the hyper-exponential distribution.

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