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ANALYSIS OF CYLINDER PRESSURE CYCLIC VARIABILITY OPERATING WITH BUTANOL BLENDS IN A DIESEL ENGINE

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ABSTRACT

Butanol is a second-generation biofuel which obtained from the biomass feedstock sources to improve the fuel properties and performance of the recent fuels. However, there are certain grey aspects in the combustion characteristics of butanol blends in various operating speeds and loads. This previous work investigated the use of mineral diesel (D), palm biodiesel (B), butanol (10%)-diesel (90%) (DBu10) and butanol (10%)-palm biodiesel (90%) (BBu10) fuels. The objectives of this study are to investigate the cyclic combustion variations of cylinder pressure profiles and peak cylinder pressure, P_{max} and analyse the combustion stabilities using recurrence plot (RP) on tested fuels using a diesel engine. The results showed that higher peak cylinder pressures were observed for butanol blends with full load at 1100 rpm. Higher cylinder pressure cyclic variability occurred at high load and speed for all test fuels, especially DBu10 with higher COV_{Pmax} values. Thus, in this case, DBu10 produced the most chaotic combustion irregularities and higher cyclic variations for the time series in those conditions. In conclusion, cylinder pressure variations in the time series were found to be affected by the fuel composition of butanol in the blends and types of fuel in engine operation.

Keywords: Cylinder pressure, cyclic variability, butanol, recurrence plot (RP), diesel engine

NONMENCLATURE

COV	coefficient of variation
RP	recurrence plot
RQA	recurrence quantification analysis
IMEP	Indicated mean effective pressure
CI	Compression ignition
P_{max}	peak cylinder pressure
N	Engine speed
deg.CA	Crank angle degree

1. INTRODUCTION

In-cylinder pressure has always been considered an important experimental diagnostic parameter in engine research and development due to its direct relation to the fuel combustion process [1]. The analysis of thermodynamic for the measured in-cylinder pressure data is a significant tool to quantify the combustion parameters of both compression and spark ignition engines. Furthermore, the in-cylinder pressure measurement could provide useful information regarding cylinder torque variability, cyclic fueling variability, thermal efficiency, intake and exhaust tuning, combustion phasing, cylinder balance, detonation and structural loading. Regarding the studies for the purposes described above, in-cylinder pressure data is averaged at each crank angle to obtain the mean at desired accuracy and used to obtain average indicated engine performance characteristics including indicated work, indicated power and IMEP.

In-cylinder pressure cyclic variations can easily be seen by plotting the pressure data for each cycle on one figure. However, the mean measured in-cylinder pressure in the experimental work is computed averagely from the numbers of the cyclic variation at a certain period. Through the measurements of the pressure-time history of consecutive cycles in the combustion chamber in the engines, the variations from

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one cycle to another do exist and can be easily seen. Since the in-cylinder pressure rate is exclusively related to the combustion, the pressure variations are caused by both chemical and physical phenomena variations that occur cyclically in the combustion process. Those chemical and physical phenomena are considered as the fuel composition, the fuel-air ratio, the changes in the residual gas fraction and the motion of unburned gas in the closed cylinder. Three identified sources that contribute to the development of cyclic variations in the cylinder are mixture composition [1,2], cyclic cylinder charging [3] and in-cylinder mixture motion [4]. The factors which belong to the mixture composition and cyclic cylinder charging influence mostly the main stage of the combustion, while the other sources play a regular role at any stage of the combustion.

The objectives of this study is to investigate the cyclic combustion variations of cylinder pressure profiles and peak cylinder pressure, P_{max} and to analyse the combustion stabilities in-cylinder pressure using recurrence plot (RP) fuelled with mineral diesel (D), palm biodiesel (PB), palm biodiesel-butanol (BBu10), and mineral diesel-butanol (DBu10) blends. These investigations were conducted at full load with a specific engine speed of 1100 rpm for 200 consecutive cycles are further analyzed and discussed in details.

2. MATERIALS AND METHODS

In this research work, palm biodiesel (B) and butanol were blended at 10% by volume of butanol for each 1 litre of palm biodiesel and mineral diesel , which denoted as DBu10 (90% mineral diesel+10% butanol) and BBu10 (90% palm biodiesel+10% butanol). The fuel properties of the blends are tested according to the ASTM standards listed in Table 1.

Table 1. Test fuel properties

Details	Testing Method (ASTM)	Mineral diesel (D)	Palm Biodiesel (B)	BBu 10	DBu 10
Density @ 20 °C g/cm³	D287	0.826	0.867	0.858	0.824
Viscosity @40 °C mm²/s	D445	5.144	7.495	6.026	3.576
Cetane number	D613	47.8	52.8	52.4	51
Flash Point (°C)	D93	60	80	74.4	56.4
Net heat of combustion (MJ/kg)	D240	44.8	38.6	37.99	43.6

This research work was conducted on a Yanmar TF120-M single cylinder diesel engine with a maximum power of 7.8 kW at 2400 rpm. The engine was coupled to a 15 kW eddy current, dump load dynamometer with a universal controller model DC5-10KW to control the engine speed and torque. Two separate fuel tanks with thermocouples and a fuel valve system were used, one for biodiesel and the other for the blends. In the fuel

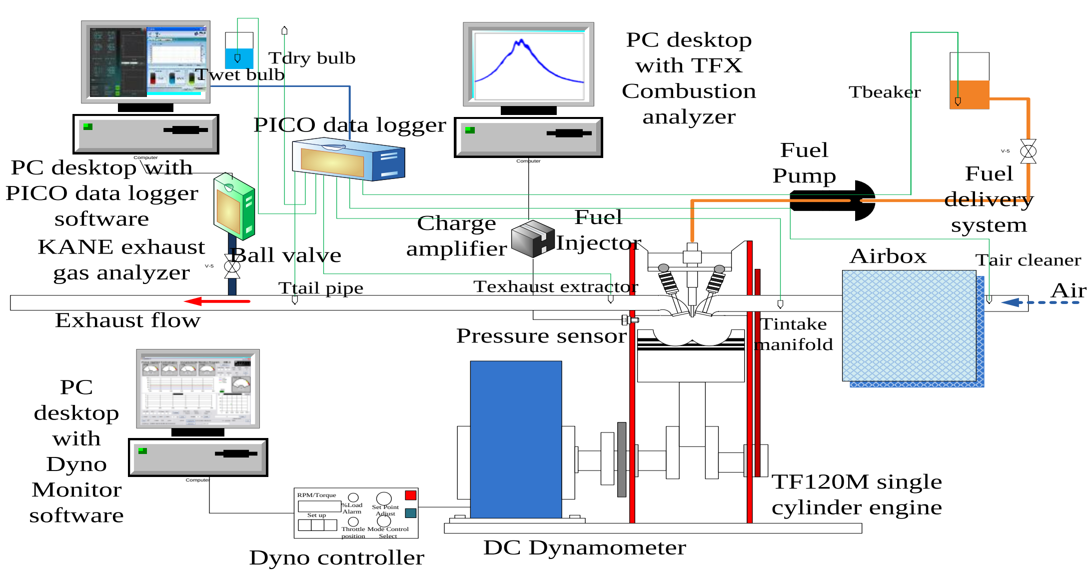

Fig 1 Engine testing set up

delivery system, a burette was used to measure the fuel consumption of both fuels. Fig. 1 illustrates the setup of the engine testing and specification of the test engine [5].

Since this work focuses on the cyclic combustion of cylinder pressure, an Optrand AutoPSI-S model C22294-Q pressure transducer was used to measure the in-cylinder pressure [5]. A magnetic crank encoder was used to obtain the signal of the crank angle degree (CA). The in-cylinder pressure recording and measurement for further analysis processes were executed using a TFX combustion analyser at the specific test condition. Each 200 consecutive cycles were analysed to evaluate the cyclic combustion using recurrence plot (RP) analysis.

3. RESULTS AND DISCUSSION

The analysis of test fuels comparison involving 200 cycles of cylinder pressure data and mean cylinder pressure are shown in Fig. 3. It can be seen from the figure that the 200-cylinder pressure cycles and mean cylinder pressure diagrams do not show any appreciable difference in profile between D, B and butanol (BBu10 and DBu10) blends. However, as expected, the pressures increase with load for all fuels at similar engine speed. The results reveal that higher combustion temperature is observed at high engine load for all fuels due to a larger amount of fuel burnt in the cylinder which is mainly attributed to the increase in temperature for the residual gas and the cylinder wall. Also, lower cyclic variations in cylinder pressure are observed with the decrease in the ignition delay [6].

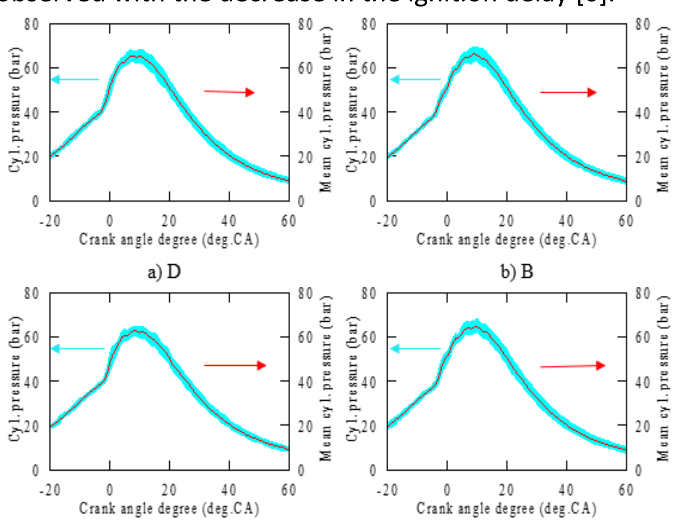

Fig. 3 Comparison of cylinder pressure cyclic variations and mean cylinder pressure with a full load at 1100 rpm

Table 3 Statistical results and percentage of relative standard error, RSE% on cylinder pressure cyclic variations at full load (N=1100 rpm)

Test fuels	Cylinder pressure, bar			Std Dev, σ	COV	RSE, %
	Mean	Max	Min			
D	65.5	68.0	63.3	0.92	0.014	0.09
B	66.2	69.2	63.5	1.08	0.016	0.11
BBu10	64.8	68.1	62.6	0.89	0.014	0.09
DBu10	63.0	64.6	61.0	0.70	0.011	0.07

In Table 3, it is observed that full load significantly increases the mean cylinder pressure for all test fuels at constant engine speed. More fuel is delivered and burnt at this point; the hence higher combustion temperature cylinder pressure are achieved. Therefore, most of the test fuels achieve higher mean cylinder pressure at this point.

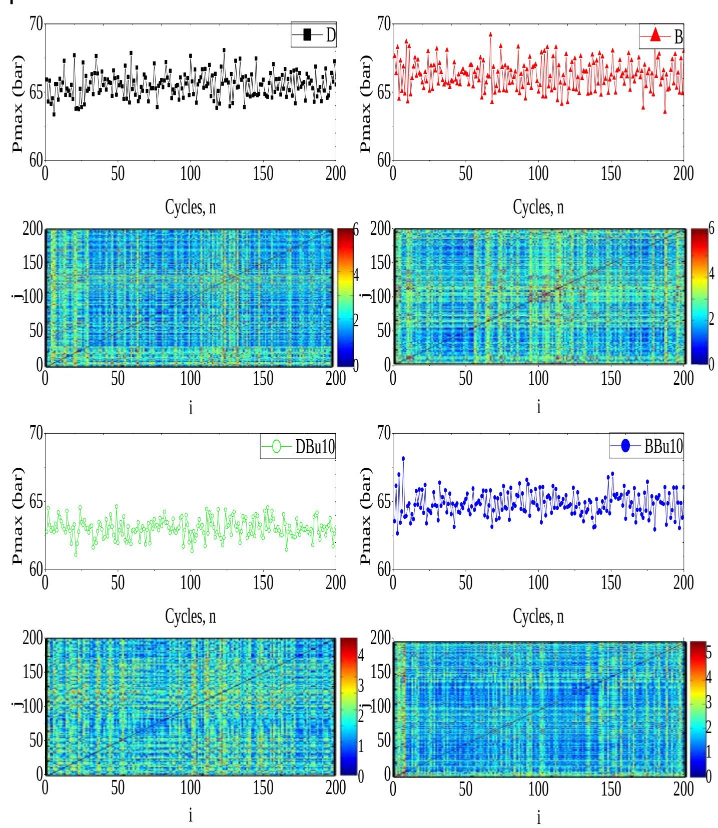

Fig. 4 Time series of peak cylinder pressure cyclic variation values, P_{max} (i) and RP with a full load at 1100 rpm

Two-dimensional dynamical graphic patterns of the P_{max} values from the RP are compared in Fig. 4. It is observed from the figure that different graphical patterns are found corresponding to the magnitude of the P_{max} data values representing all four fuels. Note that the RPs of peak cylinder pressure, P_{max} time series are inconsistent with that of a pure random process whose RP describes a uniform distribution (all blue regions). The RP patterns for all fuels are more similar to the chaotic processes whose RPs are composed of red, yellow and blue regions. Analysing Fig. 4, larger irregularities are observed in case of B, while for other fuels D, BBu10, and DBu10, smaller irregularities are found in the RPs.

Table 4 RQA parameter values for test fuels at full load, (N=1100 rpm)

Test fuels	**RQA parameters values**	
	DET	**LAM**
D	2.720	0
B	1.604	0
BBu10	3.671	0
DBu10	6.462	2.206

Note that at high load with constant engine speed, more fuel is delivered and burned at high temperature which leads to higher pressure in the cylinder [7]. Also, more chaotic combustion process are observed at this state with different fuel composition. The summary of the corresponding RQA is listed in Table 4. Note that DET and LAM are the corresponding ratios of points in diagonal and vertical lines. It is observed that larger DET and LAM values are observed for DBu10 at this operating condition which significantly leads to more deterministic structures. These quantities are connected to the stability of the engine operation in which lower cyclic variations are observed.

4. CONCLUSIONS

The conclusions for the work as follows:

- For all four fuels, there was a significant increase of cylinder pressure with full load condition at 1100 rpm. However, lower peak cylinder pressure was observed for butanol blends especially DBu10 compared to that of D and B fuels
- The COV value has an increasing trend in the presence of butanol in B and D fuels. Also, the COV values are found to be higher for butanol blends compared to that of D and Biodiesel fuels.
- Higher recurrence points are observed for DBu10 fuel compared to that of B and BBu10, which shows more engine stability is obtained at the operating condition.

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