Pamukkale Univ Muh Bilim Derg, 30(4), 429-435, 2024

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

An experimental study on cycle-to-cycle combustion variations at different speeds in a common-rail diesel engine

Ortak hatlı bir dizel motorda farklı devirlerde çevrimden çevrime yanma değişimleri üzerine deneysel bir çalışma

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Received/Geliş Tarihi: 17.12.2022 Revision/Düzeltme Tarihi: 15.08.2023 doi: 10.5505/pajes.2023.23565
Accepted/Kabul Tarihi: 12.09.2023 Research Article/Araştırma Makalesi

Abstract

The objective of this study is to experimentally investigate cyclic combustion variabilities in a four-cylinder automotive common-rail diesel engine at different engine speeds, including 1600, 1800, and 2000 rpm. The investigation evaluates the relative effects of speeds on the cyclic discrepancies in a modern diesel engine. 1000 cyclic combustion data including peak combustion pressure (Pmax), peak pressure rise rate (PRRmax) and indicated mean effective pressure (IMEP) were analyzed in the experimental study. It was found that the cyclic fluctuations in combustion pressure in each engine speed were minor, but detailed comparison of Pmax, PRRmax, and IMEP revealed noteworthy differences in the studied cycles. Higher cylinder temperatures and air movement improved combustion. Therefore, not only coefficient of variations COVs of IMEP and Pmax decreased, but also mean Pmax and PRRmax increased with increasing engine speed. On the other hand, the friction effect of the intake air reduced the positive effects of improved combustion with increasing engine speed and as a result mean IMEP decreased. COVs of IMEP and Pmax remained below 1% at all speeds, thus stable and regular combustion was maintained even in a numerous range of the cycle numbers. Pre-injection phase of fuel injection system was recognized to be effective in formation of the first peak of the combustion pressure in individual cycles. It was concluded from this study that the common-rail diesel engine generated minor cyclic discrepancies under different engine speeds.

Keywords: Cyclic variations, Combustion parameters, Common-Rail diesel engine.

Öz

Bu çalışmanın amacı, dört silindirli ortak hatlı bir otomotiv dizel motorunda 1600, 1800, 2000 d/dk.'lık devirlerde çevrimsel yanma değişimlerini deneysel olarak incelemektedir. Çalışma, bir modern dizel motorda devir sayısının çevrimsel farklılıklara bağlı etkisini ele almaktadır. Maksimum yanma basıncı (SBmaks), maksimum basınç artış oranı (BAOmaks), ve ortalama indike basınç (OİB) parametrelerini kapsayan 1000 çevrimsel yanma verisi deneysel çalışmada analiz edilmiştir. Her bir motor hızında, silindir basıncındaki çevrimsel değişimlerin minimum olduğu, ancak SBmaks, BAOmaks ve OİB detaylı olarak karşılaştırıldıklarında incelenen çevrimlerde önemli farklılıklar ortaya çıkmıştır. Daha yüksek silindir sıcaklıkları ve hava hareketleri yanmayı iyileştirmiştir. Böylece, artan motor devriyle birlikte sadece OİB ve SBmaks'ın çevrimsel değişim katsayıları (ÇDK) azalırken, aynı zamanda ortalama SBmaks ve BAOmaks artmıştır. Diğer taraftan, artan devirle birlikte emme havasının sürtünme etkisi, iyileşen yanmanın pozitif etkilerini azaltmış ve sonuç olarak ortalama OİB azalmıştır. SBmaks ve OİB'nin ÇDK'ları tüm devirlerde %1'in altında kalmıştır, böylece oldukça geniş çevrim sayılarında bile stabil ve düzenli yanma sürdürülmüştür. Her bir çevrimde, yakıt sistemi ön enjeksiyon fazının, ilk yanma basınç pikinin oluşumunda etkili olduğu gözlenmiştir. Bu çalışmadan, ortak hatlı dizel motorun farklı devirlerde küçük çevrimsel farklılıklar meydana getirdiği sonucuna varılmıştır.

Anahtar kelimeler: Çevrimsel değişimler, Yanma parametreleri, Ortak hatlı dizel motor.

1 Introduction

Modern compression ignition (CI) engines are widely used today in transport and energy requirement facilities, such as modern automotive vehicles, maritime transport sector, and stationary generator applications. Their high thermal efficiency, better fuel economy, and lower emission aspects compared to earlier engine generations make them preferable devices. The limited knowledge of the inconsistencies in the event of combustion compels researchers to draw comprehensize insights and new conclusions. Therefore, a deeper understanding of in-cylinder process is required to make CI engines run more efficiently and cleanly.

One of the key aspects of the diesel cycle is the combustion process, which refers to the sequence of events that occurs within the engine during the power stroke. This process is critical to the performance of the engine, and can be affected through a number of factors, including the engine working parameters, the fuel injection system, and the injection timing.

Cycle-to-cycle variabilities in CI engines are mainly responsible for sensible vibration formation. Unstable and vibrational operations in CI engines are closely related to cycle-to-cycle combustion differences. During sequential cycles, regional air-fuel mixture discrepancies in combustion chamber, residual gas concentration mixed with the new fresh air, rich or lean combustion zones in the combustion chamber, early flame development conditions, ignition delay, fuel type and injection characteristics are main sources of the cycle-to-cycle variabilities [1],[2]. Engine output, combustion noise, and emissions are always affected by the cyclic variations [3]. The fastest burning cycles limits to operate with the higher

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compression ratio because of being most likely to knock at high load. At low loads, the slowest burning cycles are prone to incomplete combustion, leading to deficits of fuel conversion efficiency and undesirable amount of the unburned hydrocarbon emissions. Discrepancies in combustion process confine the work production per cycle strictly associated with the variations in engine speed or torque output, which comparatively affecting the vehicle drivability [4]. If the cyclic discrepancies are minimized, the engine efficiency would be remarkably enhanced even if the engine runs at part loads [4]. Excessive variations in combustion cycles, particularly at higher loads, may cause damage to engine or reduce the engine lifetime [5].

In a CI engine, the charge is ignited through the high pressure and temperature generated by the compression of the air. However, the exact point at which the fuel ignites can vary in the cylinder, leading to differences in the rate and intensity of the combustion. This can be resulted in variations in level of the power generated by the engine and the efficiency of the combustion process [6].

Different engine parameters have a significant impact on cyclic variabilities in internal combustion engines. Hamai et al. [7] investigated effects of main operation parameters on cyclic variations in a spark ignition (SI) engine. They revealed that air/fuel ratio (A/F) was strongly correlated with the IMEP and heat releasing delay over 50 cycles. That is, the richer the mixture near the spark plug, the higher the IMEP and the lower the heat releasing delay in individual cycles. Yu et al. [8] executed experimentally a study in an SI engine with 10% hydrogen (H_2) fraction under H_2 direct injection mode for lean burn. They found that COV IMEP increased with increment of excess air ratio, and cyclic variations were reduced and combustion stability was aroused notably with H_2 addition. Shere and Subramanian [9] conducted some tests in a single cylinder common-rail direct injection (CRDI) engine at 2200 rpm and full load. The authors investigated effects of fuel type and different injection timings which are 12^{o} and15^{o} before top dead center (TDC) in the engine fuelled with dimethyl ether (DME). In the study, cyclic variations of Pmax, PRRmax, and IMEP for 100 consecutive cycles were reported. For only diesel operation at different injection timings it was found that COV of Pmax values were between 2.7% and 3.2%, and COV of IMEP values were between 1.86% and 1.52%. In addition, they also showed that fuel type had a strong effect on cyclic variabilities. Gürbüz et al. [10] reported that H_2 usage in SI engine provided more stable engine operation, by decreasing the COV of IMEP. Şanlı and Yılmaz [11] investigated effects of H_2 fumigation from 10 lpm (liter per minute) to 50 lpm on cyclic variations of a CRDI diesel engine at different engine loads. They reported that combustion process for all H_2 fumigation ranges was quite stable. The COVs of IMEP, Pmax, and 10-90 of mass fraction burned were within the limit of 3%. Yasin et al. [12] investigated 200 consecutive cylinder pressure and IMEP variations in a diesel engine fueled with biodiesel and alcohol blends. COV of IMEP value of about 2% with diesel operation was lower than the results obtained with biodiesel and alcohol blends. Ceviz et al. [13] reported that biodiesel presence in diesel fuel led to lower COV of Pmax and COV of IMEP at different engine speeds. On the other hand, it was found that biodiesel presence increased COV of Pmax at low engine speeds. Lü et al. [14] investigated cyclic variations in n-heptane fuelled homogeneous charge compression ignition (HCCI) engine under partial combustion, normal combustion, and knock combustion. The COVs of Pmax, PRRmax, and IMEP at normal and partial combustion are minimal, while they considerably increased at knock combustion. The COVs of IMEP and thermal efficiency are minimal at richer mixtures. Sjöberg et al. [15] examined effects of retarding the combustion phase by decreasing intake temperature or decreasing the coolant temperature on smoothing of heat release rates in an HCCI engine, combined with experimental and simulation analyses. Authors reported that overly retarding of the combustion phase was resulted in unstable operation with partial-burnt cycles and undesired IMEP fluctuations, knocking cycles, and enhanced emissions of hydrocarbon and carbon monoxide. Yang et al. [16] investigated disturbance sources of combustion process together with cyclic variations aroused by fuel injection system. The chief sources according to investigation results of combustion disturbances are variations in the common rail pressure as well as injector current. Sen et al. [17] investigated the variations of IMEP in a diesel engine at different engine speeds. They found that under different engine speeds strong periodicities appear in low-frequency bands and may continue over many cycles, whereas the intermittency may continue at higher frequencies.

Since various engine parameters have different impacts on the cycle-to-cycle variations, it can be aroused different problems on combustion stability and drivability conditions; therefore, more detailed investigations are required. In addition, in the light of above literature review, few studies related effects of engine speed on cyclic combustion variations were found. In this regard, this study investigates and discusses the relationship between degree of cyclic variations and engine speed in a common-rail diesel engine.

2 Material and methods

In this study, a commercial turbocharged CI engine (K9K 700) was used. The EGR system was disabled so as not to affect the test results. A Cussons, model P8602 dynamometer is used in order to load the test engine. A cylinder pressure sensor and a fuel pressure sensor were used to collect pressure data. A pressure signal was taken in every 1 ^{o}CA, 720 signals generated 1 cycle data. The software was used to save and analyze the pressure data. The software was set to collect 1000 cycle data. When the engine reached to steady-state conditions for each test, data collection was started and automatically stopped by the software when 1000 subsequent combustion cycles had been completed. Schematic illustration of the test bench is given in Figure 1.

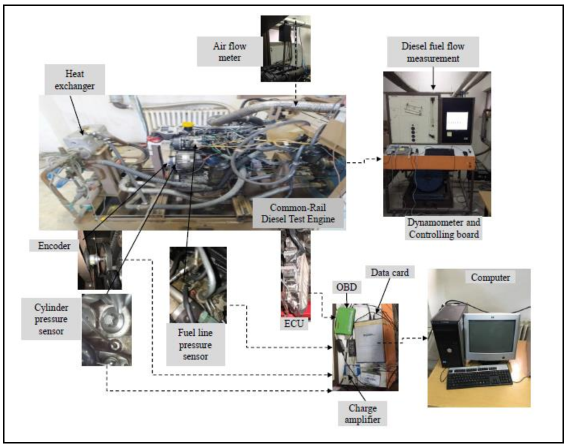

Figure 1. Schematic illustration of the test system.

Main specifications of the test engine end the pressure sensors can be respectively seen at Table 1 and Table 2. Kistler charge amplifier (model 4067 C2000S) was used to amplify the fuel line pressure signals. Diesel fuel purchased from the Petrol Ofisi gas station was used in the tests.

Table 1. Specifications of test engine.

Type	Inline, four stroke, turbocharged
Cylinder volume	1461 cm³
Number of cylinders	4
Maximum power	48 kW (4000 rpm)
Maximum torque	160 Nm (1750 rpm)
Compression ratio	18.25
Fuel injection	Common-rail

Table 2. Specifications of sensors.

	Cylinder Pressure Sensor		Fuel Line Sensor	
Brand/Model	Optrand	33288 GPA	Kistler	C6533 A11
Range	bar	0-200	bar	0-2000
Linearity	% FSO	±1	% FSO	<±0,5
Operating Temperature	°C	-40-300	°C	20 -120
Output signal	V DC	0,5-4,5	mA	4-20
Natural frequency	kHz	>120 kHz	kHz	>100
Overload	bar	400	bar	2 500

A National Instruments 6343 model data collecting card was used to acquire fuel line and cylinder pressure data over 1000 cycles. All tests were conducted at revolutions of 1600, 1800 and 2000 rpm at a constant load of 60 Nm. The experiments were performed at around 80 ±5 °C. Temperatures at different points on the test engine were measured via K-type thermocouples.

In analyzing of the cycles, coefficient of variation (COV) is computed from Equation (1).

$$COV\_X = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}}{\bar{X}} 100 \tag{1}$$

Where n symbolizes number of cycles, X_i is value of random combustion parameter (Pmax or IMEP in this study) in i^{th} cycle, and $\bar{X}$ denotes the mean value of n combustion parameters. Pmax was determined from the experimental data, and IMEP is defined by using instantaneous combustion pressure (P) and volume (V), and displacement volume (V_d) presented in Equation (2).

$$IMEP = \frac{\oint P.dV}{V_d} \tag{2}$$

3 Results and discussion

Combustion pressure measurement is one of the main tools used to study the fundamental burning characteristics in today's test engines. Figure 2 presents sequential combustion pressure traces versus crank angle during 1000 cycles for different speeds. It is clear from the Figure 2 that similar cycle-to-cycle cylinder pressures were produced at a constant speed.

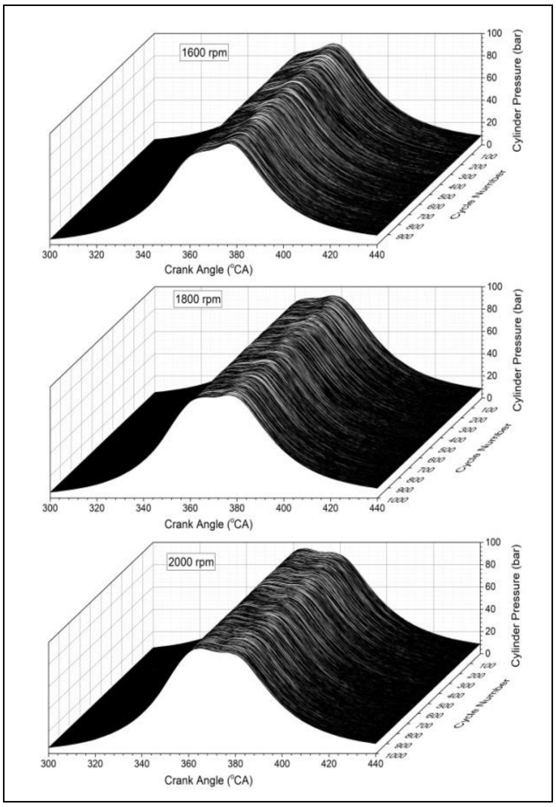

Figure 2. Sequential variabilities of cylinder pressure curves over 1000 cycles for different engine speeds.

However, considering the average value of the cylinder pressure, it raised when the engine speed is increased, which was probably owing to better mixing formation by improving the pilot and main injection characteristics which affected the first peak of cylinder pressure in whole cycles. The test engine has two fuel injection phases. These are pre-injection and main injection [18]-[20]. With increasing engine speed, the engine management system would advance the fuel injection timing. Otherwise, the combustion process may be delayed due to an increase in the mean piston speed, resulting in poor combustion efficiency. CI engines generally give more regular and stable cyclic combustion discrepancies than SI engines [2], [3]. For instance, Chen et al. [21] reported substantial fluctuations in the cylinder pressure over 100 consecutive cycles under lean burn conditions in an SI engine fuelled with natural gas and methanol. They documented remarkable cylinder pressure fluctuations for each fuel operation. Similarly, Gupta and Mittal [22] demonstrated that the cylinder pressure traces in methane-fuelled SI engine unsteadily varied during 120 consecutive cycles. They reported that the cyclic pressure fluctuations were diminished with increasing compression ratio.

Figure 3 illustrates cycle-by-cycle variabilities of Pmax and also indicates mean values of Pmax under different speeds. It was seen that Pmax values varied significantly from cycle to cycle at a constant speed. Maximum and minimum values of the peak cylinder pressures were detected between 92.35 bar with 388th cycle and 89.01 bar with 197th cycle at 1600 rpm, and between 93.77 bar with 775th cycle and 90.67 bar with 14th cycle at 1800 rpm, and 95.80 bar with 917th cycle and 93.89 bar with 108th cycle at 2000 rpm.

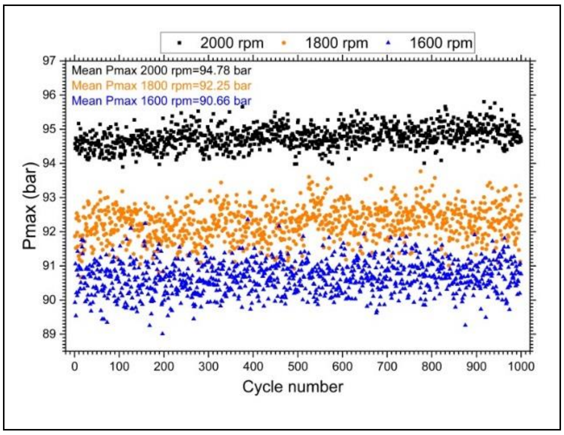

Figure 3. Cyclic variations of Pmax over 1000 individual cycles for different engine speeds.

Figure 3 also indicates that the mean value of Pmax is elevated with the engine speed, which is consistent with the literature study [23]. It can be emphasized that with increasing the engine speed, both air movement in the cylinders and injection pressure increase. This means that the sprayed fuel droplets are more evenly distributed in the cylinder [24]. Clearly, it was resulted in stronger diesel combustion, thus leading to higher peak pressures with increasing the speed.

Figure 4 exhibits relationship between Pmax values and corresponding crank angles at different engine speeds. As indicated earlier, peak values of the cylinder pressure increased with enhanced engine speed. At low and medium speeds, the highest values of the cylinder pressure were achieved at 16-18 °CA after TDC. At higher speed, they happened at 4-5 °CA after TDC. These results may be due to the dynamic injection strategies of the engine management system. At higher engine speeds, the injection process starts earlier, and more fuel is needed to improve the crank revolution. Increase in amount of the pre-injected fuel shifts the first peak pressure nearer TDC. As raising the engine speed, the compression pressure and gas temperature increase due to enhancing the air swirl, which in turn increases the heat loss to the jacket water [15]. This phenomenon can relatively affect engine performance since thermal efficiency of the engine reduces when the heat loss from the combustion chamber is increased. COV of Pmax, presented in Figure 5, is observed to be reduced notably with increasing the engine speed. When the crank revolution was increased from 1600 r/min to 2000 r/min, COV of Pmax was diminished from 0.52% to 0.33%, meaning that cyclic fluctuations of Pmax were noticeably decreased and the drivability was enhanced with elevated speed, which is due to improved combustion stability aroused by combined effects of better A/F mixture, higher combustion temperature and improved turbulent flow [23].

Figure 6 shows pressure fluctuations in fuel line in each cycle at the speed of 2000 r/min. It is emphasized that one of the key issues contributing to cyclic fluctuations in diesel burning is the fuel injection process [1], [20]. In a CI engine, fuel is introduced directly into the cylinder and is ignited by the charge with high temperature. However, the fuel injection process, as shown in Figure 6, is not always uniform among the sequential cycles. This can result in differences in the fraction and timing of fuel injection for each working cycle, thus leading to variances in the combustion pressure and the generation of power [21].

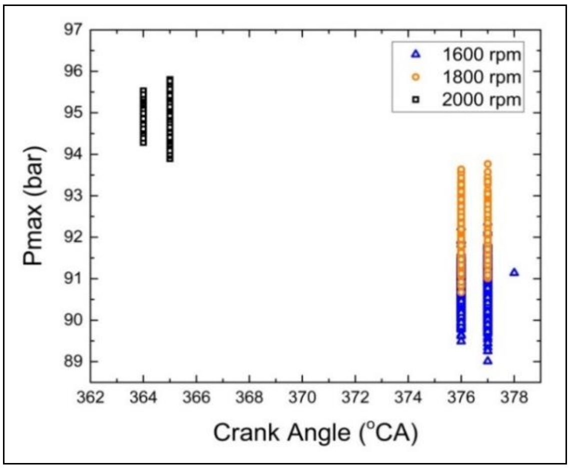

Figure 4. Pmax and CA locations for different engine speeds.

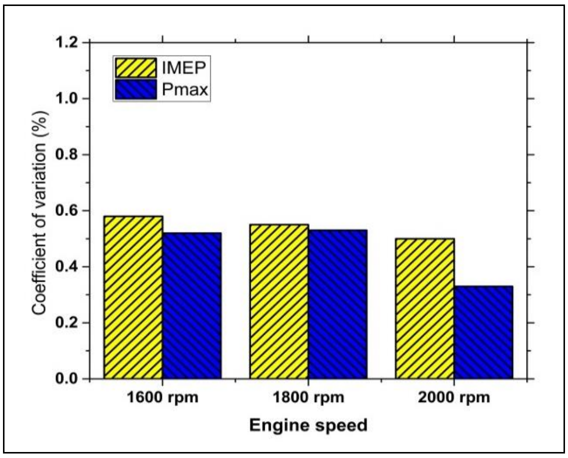

Figure 5. COV of IMEP and Pmax variations under various engine speeds.

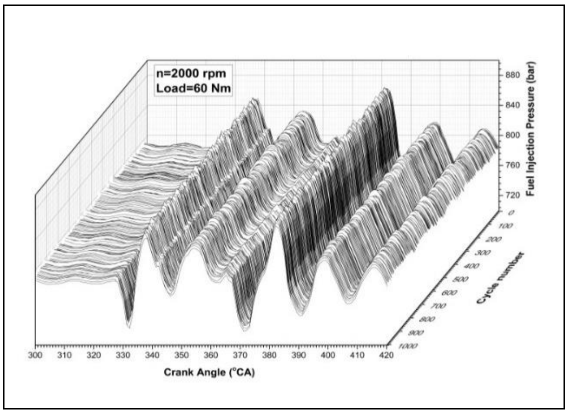

Figure 6. Individual pressure variabilities in fuel line over 1000 cycles for 2000 r/min.

Pressure rise rate is an important tool used for determining the engine knock characteristics. It is calculated from instantaneous cylinder pressure traces. Its peak value in each cycle is evaluated in this study and presented in Figure 7. It was found that as increasing the engine speed, cyclic PRRmax values showed a significant increase. Mean values of PRRmax for 1000 cycles were found 3.36 bar/°CA at 2000 rpm, 3.19 bar/°CA at 1800 rpm, and 2.98 bar/°CA at 1600 rpm. At high speed, boosted turbulence intensity and air movement raise the mixture formation degree of the charge.

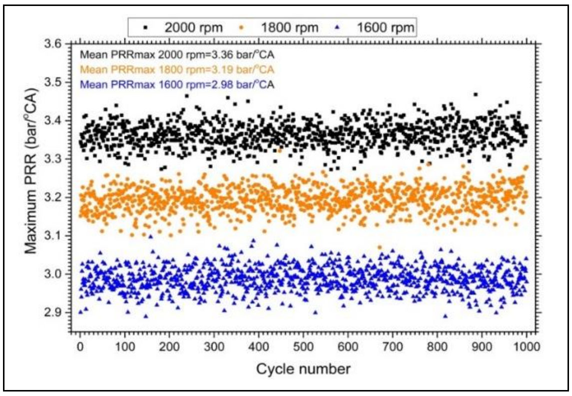

Figure 7. Sequential variations of maximum PRR over 1000 cycles for different engine speeds.

Consequently, burning spreads promptly. This can build up the high combustion pressure leading to significant variations in instantaneous pressure rises. Lastly, the highest value among the peak pressure rise rates in entire operation conditions was found 3.46 bar/°CA at 2000 rpm, which implies no knocking cycle existed during the tests, based on limit defined in the literature [6].

IMEP is the mean effective pressure determined by cylinder pressure traces over the engine cycle. It is used to assess the cyclical burning variabilities, and its COV value is a valuable magnitude to achieve reasonable remarks about the combustion stability for a given engine operating condition [28]. Figure 8 represents the impact of engine speed on cyclic discrepancies in IMEP. As can be seen, IMEP significantly varied from one cycle to another. It is clear from the Figure 8 that IMEP values at 1800 rpm were higher than those at 1600 and 2000 rpms due to probably operating at the best torque revolution obtained in 1750 rpm. At the close speed conditions to the maximum best torque, the best engine performance is obtained due to operating at better volumetric efficiency and minimal fuel consumption. As a result, the combustion process can be significantly improved, and IMEP at 1800 rpm is obviously expected larger than others. At elevated speed of 2000 rpm, cycle time for efficient combustion process was shortened, and dilution effect of the residual exhaust gases aroused [23]. Furthermore, the airflow was lower due to viscous friction in the intake manifold, leading to inefficient combustion. Thus, effective outcomes of IMEP in subsequent cycles were partially reduced; as a result, mean IMEP was relatively lower.

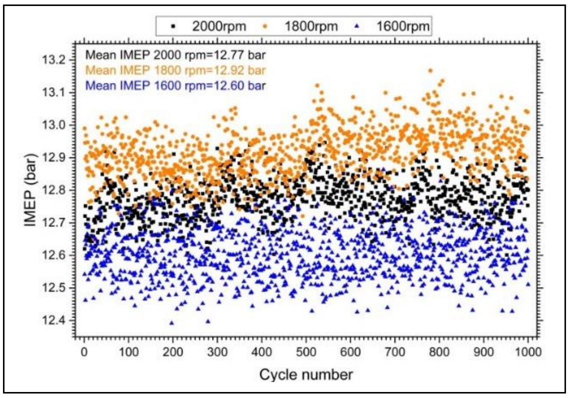

Figure 8. Sequential variations of maximum PRR over 1000 cycles at various crank revolutions.

It was shown during 1000 cycles that some of the cycles adopt an important rise in IMEP, while some of them do conversely. Maximum and minimum values of IMEP and their corresponding cycle number were respectively detected as 12.99 bar in 994th cycle and 12.58 bar in 145th cycle at 2000 rpm, and 13.17 bar in 780th cycle and 12.65 bar in 22nd cycle at 1800 rpm, and 12.86 bar in 673th cycle and 12.39 bar in 197th cycle at 1600 rpm. This corresponds to respective IMEP differences of 0.41, 0.52, and 0.47 bar at the speeds of 2000, 1800, and 1600 rpm. As raising the crank revolution, turbulent movement of the air at intake and compression strokes significantly increases the phenomena of tumble and squish. Whereas, as increasing the engine speed intake air amount in the intake manifold weakens partly due to increasing the friction losses inside the intake channels originated from the viscous effects of the fluid, as a result of that, mass of air drawn into the cylinders decreases and makes an opposite influence on cycle efficiency. Consecuently, IMEP can be weakened by increased crank revolution. COV of IMEP was decreased as increasing the crank revolution, as shown in Figure 5 previously. When raising the speed from 1600 rpm to 2000 rpm, COV of IMEP was diminished from 0.58% to 0.50%. Faster crank revolution provided more stable operation over the combustion cycles of the engine. These values are well coincided with studies performed by Ghadikolaei et al. [29] and Ozkan [30]. It is also expected that COV of IMEP does not exceed 10% that interprets the poor drivability [6],[31]. However, such COV of IMEP and Pmax behavior with engine revolution was not observed before in the literature studies conducted on CI engines fuelled with various fuels. On the contrary, Wang et al. [32] found in a NG run SI engine that COVs of peak pressure and IMEP enhanced with increasing engine speed. Besides, COV of IMEP was over 1% while COV of Pmax was upper than 6%. Karvountzis-Kontakiotis et al. [33] documented similar results related to the COVs of IMEP and Pmax in an SI engine. Also, in the case of maximum best torque, they obtained the lowest deviance and the lowest COV of IMEP. Accordingly, this study also supports the general conclusion of that the CI engines produce rather steady cyclic variations in comparison to SI engines [2],[3],[32],[34],[35].

4 Conclusions

Common rail diesel engine was run under different engine speeds to analyze cycle-to-cycle combustion variations. It may be concluded below results from this study.

Mean cylinder pressure enhanced as increasing the engine speed. Average cylinder pressures were 90.66 bar, 92.25 bar, and 94.78 bar at 1600, 1800, and 2000 rpm, respectively. Cyclic Pmax values during 1000 cycles were found to be noticeably variable. Corresponding crank angles of the Pmax in each cycle was found quite close to each other, and with the speed of 2000 rpm they were advanced due to effectiveness of pre-injection existence in the common rail fuel system. COV of Pmax reduced with increasing engine speed. Its value was 0.52 at 1600 rpm and 0.33 at 2000 rpm. PRR values in each cycle remained below the diesel-knock limit. With increasing speed, mean PRRmax values increased, which were respectively 2.98 bar/°CA, 3.19 bar/°CA, and 3.36 bar/°CA at corresponding speeds of 1600, 1800, and 2000 rpm.

COV of IMEP values were obtained as 0.41, 0.52, and 0.47 bar at 1600, 1800, and 2000 rpm speeds, respectively. The highest mean IMEP value was obtained at 1800 rpm, and then followed by 2000 rpm and 1600 rpm, with the corresponding mean IMEP values of 12.92 bar, 12.77 bar and 12.60 bar.

Overall, the presented results revealed that the engine speed has minimal effect on the cyclic combustion variations of CRDI engine, and stable and regular burning based on the pressure related combustion parameters is preserved under different engine speeds. Increasing the engine speed reduced the COVs of IMEP and Pmax. According to the results, the optimum engine speed among the test conditions is 1800 rpm.

This study was performed within limited torque and speed range. Future studies can be conducted over a wider range of engine torque and speed. More precise results can also be achieved by using a crank encoder with higher resolution.

5 Symbols and nomenclature

A/F	:	Air-fuel ratio,
CA	:	Crank angle (°)
CI	:	Compression ignition
TDC	:	Top dead center,
COV	:	Coefficient of variation,
SI	:	Spark ignition,
rpm	:	revolution per minute (r/min),
CRDI	:	Common rail direct injection
HCCI	:	Homogeneous charge compression ignition
H_2	:	Hydrogen gas
$IMEP$	:	Indicated mean effective pressure (bar),
NG	:	Natural gas
n	:	Number of cycles,
$Pmax$	:	Peak combustion pressure (bar),
$PRRmax$	:	Peak rate of pressure rise (bar/°CA),
V_d	:	Displacement volume (m^3),
$\bar{X}$	:	Average of random combustion parameter.

6 Ethics committee approval and conflict of interest statement

“There is no need for permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person or institution in the article prepared”.

7 Author contribution statements

In this study, Ali ŞANLI involves in conceptualization, methodology, literature review, analyzing the data, writing and visualization, and İlker Turgut YILMAZ involves in supervising, experimental study, validating the results, and reviewing the writing, spell-check and editing.

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