Experimental study on knocking combustion in compression-ignition engines under high-altitude conditions

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Abstract. Diesel engine combustion becomes very rough or even detonation under high altitude conditions, which is harmful to components durability. In this study, combustion characteristics were experimentally investigated on a V6 heavy-duty diesel engine using a plateau simulation test bench to simulate altitude conditions of 1000 m, 3000 m and 4500 m. Results show that extremely high peak pressure rise rates of above 50 bar/°CA exist at low speeds under the altitude of 4500 m. This indicates that not only does knocking combustion exist in spark-ignition (SI) engines, but also can be found in compression-ignition (CI) engines. Knock intensity (KI) is calculated by the pressure oscillation with high-pass filtering (HPF). Approach of cycle to cycle variation was adopted to study combustion characteristics on the comparisons of knock and non-knock states. Also, the correlation between KI and peak pressure rise rate was revealed through the linear regression method.

1. Introduction

Various kinds of failure of internal combustion engines can be resulted by knocking combustion, such as piston crown melting, piston ring sticking, cylinder bore scuffing, piston ring-land cracking, cylinder head gasket leakage and cylinder head erosion [1]. As an inherent problem in SI engines, knocking combustion is commonly considered as the auto-ignition in the end gas, leading to the high-frequency pressure oscillation and noise. In recent years super-knock has become a challenge for the high-boosted SI engine design in the low-speed, high-load operating conditions [2,3]. Super-knock is triggered by the pre-ignition stem from the “hotspot” such as oil droplets, particles in the combustion chamber other than spark [1]. As illustrated in figure 1, distinguished from the conventional knock, the maximum of pressure rise in the super-knock condition can be more than an order.

Similarly driven by the extremely high pressure rise rates, “diesel knock” is given the name to the strong pressure oscillation, destructive vibration and audible noise. Moreover, severe knocking combustion frequently occurs in homogeneous-charge compression-ignition (HCCI), premixed-charge compression-ignition (PCCI), and partially premixed compression-ignition (PPC) in high-load operation [4]. As described in the names of HCCI, PCCI and PPC, the premixed charge plays in important role in the diesel knocking combustion. A large amount of premixed charge is generated by the long ignition delay before the main combustion, leading to the diesel knock [5]. During this period, pressure waves are firstly generated by local explosions occurred at the places with local higher fuel concentration and/or temperature. Then local pressure and temperature near the combustion wave front can be increased by the compression of pressure fluctuation when pressure waves transmit across the remaining unburned gas [6]. In particular, when local explosion occurs near the cylinder wall, the
pressure fluctuation is enhanced by reflection on the wall. Under this circumstance, a sudden high increase of pressure and temperature tends to cause the surface erosion of piston ring-land [7].

![Figure 1. Three typical combustion pressures traces in boost SI engines (adapted from [1]).](image)

As mentioned above, pressure oscillation in IC engines is known as induction from the acoustic resonance resulted from end-gas auto-ignition in the combustion chamber [4]. The pressure oscillation patterns in a cylindrical cavity were proven to follow the classical acoustic Draper’s “drum mode” [8]. Thus, a simple analytical solution of vibration frequencies $f_{m,n}$ for a cylindrical combustion chamber is given as

$$ f_{m,n} = \alpha_{m,n} \frac{c}{nB} $$

(1)

where the integers $m,n$ represent the circumferential and radial mode numbers, respectively, $\alpha_{m,n}$ denotes the vibration mode factor according to Bessel’s equations, $c$ is the local speed of sound, and $B$ is the cylinder bore. Although the simplified model above is in a way different from the real geometry of the combustion chamber and the thermodynamic state, this method is a practical way to the prediction of knocking frequencies [8].

The other two important parameters to describe the knock behavior, peak pressure rise rate (PPRR) and knock intensity (KI) are calculated through the in-cylinder pressure signal. KI is calculated by the pressure oscillation by high-pass filtering (HPF) and the equation is shown as below:

$$ KI = \max(p_{HPF}) - \min(p_{HPF}) $$

(2)

As mentioned before, the long ignition delay is cline to generate diesel knock. Under the higher attitudes, owing to the reduction of molecular concentration of oxygen, longer ignition delay and premixed-phase combustion were observed [9]. Wang et al. [10] explored that the brake thermal efficiency decreases by about 20% as the high-altitude increases from 3300m to 4500 m in moderate load and speed below 1200rpm conditions in a 6.7 L heavy-duty turbocharged, common-rail diesel engine on a mobile test bench. Retarded combustion resulted in lower peak in-cylinder pressure, mean effective pressure, and thermal efficiency due to the reduced intake air temperature in a high altitude. Besides, the cycle-to-cycle variation (COV) of the IMEP also worsens with the increase of altitude. Kan et al. [11] indicated that the COV of the IMEP increased by 0.6% for every 1000m rise in altitude with the effect of mixture heterogeneity in high altitudes in a 2.8L V6 heavy-duty diesel engine. Effects of fuel properties on the combustion characteristics and cycle to cycle variation were studied by Cai et al. [12] and Zhang et al. [13]. Furthermore, as shown in figure 3, severe piston erosion was found at the valve pocket and piston topland in the diesel engines designed by China North Engine
Research Institute at the altitude around 4500m, although no damage in the sea level or at the altitude of 1000m.

![Figure 2. Illustration of knock intensity.](image)

In this study, on the purpose of exploration on the combustion phenomenon under the condition of piston erosion, a V6 heavy-duty intercooled-turbocharged diesel engine was used with an intake and exhaust pressure controlled by a plateau simulation test system to simulate altitude conditions at 1000m, 3000 m, and 4500m. Effects of altitude on the combustion characteristics such as brake thermal efficiency, excess air ratio, maximum combustion pressure and peak pressure rise rate were made at various altitudes. Comparisons of cycle-to-cycle variation of peak pressure rise rate at the knock and non-knock states were made at various altitudes. And the linear relationship of KI and maximum in-cylinder pressure rise rate was obtained in order to find a practical way to attenuate the occurrence of piston erosion.

![Figure 3. Illustration of typical piston erosion of diesel engines at the altitude around 4500m. Severe piston erosion was found at the valve pocket and piston topland.](image)

2. Experimental setup
Detailed test bench has been described in [11]. An Imtech™ plateau simulation test system was used in this study, with atmospheric pressure control ranging from 57.6 kPa to 89 kPa for simulation of 1000 to 4500m altitude conditions. As shown in figure 4, after air filter ambient air passed through an inlet drying device, and then intake humidity was adjusted by a humidity regulator. And intake and exhaust pressure were adjusted by a frequency conversion fan and exhaust fan, respectively. And intake and exhaust temperature were controlled by an inlet temperature regulator and the exhaust cooler.

Com bustion test system mainly contains in-cylinder pressure sensor and combustion analyzer. A water-cooled piezoelectric crystal sensor Kistler™ 6061B was installed on the cylinder head of first cylinder to collect the instantaneous in-cylinder pressure. This sensor is a high precision cylinder pressure sensor with thermal-shock 0.2 bar, sensitivity-25 pC/bar and natural frequency 90 kHz, which is available for knock detection. The combustion analyzer DEWETRON™ 5000 was adopted with a sampling frequency of 0.375°CA was applied to store and process the transient data. At least 120
cycles of in-cylinder pressure were stored at each operation point. The engine used in this research was a V6 DI heavy-duty intercooled-turbocharged diesel engine, as listed in table 1.

![Image](image.png)

**Figure 4.** The plateau simulation test system (adapted from [11]).

**Table 1.** Engine specifications.

| Item              | Value                                      |
|-------------------|--------------------------------------------|
| Engine type       | V-type 6 cylinders, intercooled, turbo-charged |
| Displacement      | 2.82L                                      |
| Compression ratio | 13.5                                       |
| Rated speed       | 2200 rpm                                   |

Experiments were conducted at three altitudes including 1000m, 3000m and 4500m. Before any test started, related devices were adjusted to the targeted status. The test engine was fully warmed. The combustion analyzer was zeroed and stabilized according to the manufacturer’s requirements. Ambient conditions during the tests at different altitudes are listed in table 2.

**Table 2.** Ambient pressures at varied altitudes.

| Simulated Pressure (kPa) | Altitude (m) |
|--------------------------|--------------|
| 88.9                     | 1000         |
| 70.1                     | 3000         |
| 57.6                     | 4500         |

The operation of experiments was carried out based on the requirements of machinery on plateau Part 1 for internal combustion engines according to the national standard of China GB/T 20969.1-2007. The inlet temperature and relative humidity were controlled at 298 K and 40%, which were simulated according to table 2 at altitudes of 1000m, 3000m and 4500m. Under different stimulated altitude conditions, the test prototype adopted the fuel delivery advance angle of -27°CA ATDC.
3. Uncertainty
This bench test was operated in North China in July, when local temperature was around 298K. Also, the ambient temperature in the laboratory was maintained through a circulation air supply system. The inlet temperature was fixed at 298 K with an error of ±1 K, so the uncertainty in the temperature control systems can be ignored. The precision of pressure control system was ±0.5 kPa. Due to the difference between simulated altitude and actual atmospheric conditions, the error of intake pressure control system was mainly resulted from the air leakage, slightly above 1% [11]. The other uncertainties came from the measurement precision of the apparatus. The precision for engine speed control and torque control was ±1 r/min and 15 Nm for the engine dynamometer. The precision of fuel consumption meter was 1%, whose repeatability was 0.5%.

4. Results and Discussions

4.1. Effect on brake thermal efficiency
The brake thermal efficiency is given as

$$\eta = \frac{T_q}{m_{fuel} LHV} \times 100\%$$  \hspace{1cm} (3)

where, $\eta$ is the brake thermal efficiency of the test engine; Tq (Nm) is the brake torque of the test engine, r (r/min) denotes the engine speed, $m_{fuel}$ (kg/h) denotes the mass flow of diesel; LHV (MJ/kg) is the low heat value of the diesel.

![Figure 5](image)

Figure 5. Brake thermal efficiency at various altitudes. (a)1000m, (b) 3000m, (c) 4500m.

Figure 5 illustrates the brake thermal efficiency (BTE) measured at three altitudes of 1000m, 3000m and 4500m, respectively. Overall, the BTE decreases as the altitude increases. Generally, the BTE enhances as the increase of load and speed at the same altitude. Particularly, at the altitude of
1000m, the engine reached the maximum BTE of 37% when it was running at the rated condition and maximum torque point. At the altitude of 3000m and 4500m, the maximum BTE reduces to 35% and 33%, respectively.

As known that over rich mixture would worsen the combustion efficiency and thereby the BTE reduced. Generally, it is indicated that the higher the load, the lower the excess air ratio as shown in figure 6. With regard to the effect of altitude, the p\text{max} reduces as the altitude increases generally due to the reduction of intake pressure. This trend is closely related with the operation of turbocharger at high altitude. Due to the reduction of inlet pressure at high altitude, the fresh charge sucked into cylinder is still diluted comparing with the sea level condition although turbocharger attenuates the decrease of intake pressure to some extent. The dilution of charge is directly resulted in the reduction of excess air ratio

4.2. Effect on maximum combustion pressure

Figure 7 shows the maximum combustion pressure (p\text{max}) measured at three altitudes of 1000m, 3000m and 4500m, respectively. It is mainly clear that the higher the load, the higher the p\text{max}. With regard to the effect of altitude, p\text{max} decreases as the altitude increases generally due to the reduction of intake pressure.

![Figure 6. Excess air ratio at various altitudes. (a)1000m, (b) 3000m, (c) 4500m.](image-url)
and worsening of combustion as shown in figure 3 and figure 6, which leads to less exhaust energy delivered to the turbine and thus less effective of turbocharger. Thus, the descent in efficiency of turbocharger, lower of intake pressure and worsen of combustion form a vicious cycle.

![Figure 7. Maximum combustion pressure at various altitudes. (a)1000m, (b) 3000m, (c) 4500m.](image)

It is shown in figure 7b and figure 7c highlight a dramatic variation in the moderate load and speeds between 1000rpm and 1200rpm, when an irregular increase in $p_{\text{max}}$ can be found. This is mainly resulted from the inefficiency of turbocharger mentioned above and will be further discussed in the following analyses of peak pressure rise rate and its cycle to cycle variation.

4.3. Effect on peak pressure rise rate

Figure 8 shows the cycle-average of the peak pressure rise rate (PPRR) calculated at three altitudes of 1000m, 3000m and 4500m, respectively. It is interesting that the zone of high PPRR ranging from 20bar$^{\circ}\text{CA}$ to 30bar$^{\circ}\text{CA}$ concentrates on the conditions of 40% to 60% of maximum of torque as a whole at the altitude of 1000m and 3000m as shown in figure 8a and figure 8b. A slightly increase of PPRR can be observed when the altitude changes from 1000m to 3000m. However, a sharp increase of PPRR can be found at the altitude of 4500m, compared with these two altitudes. It is markedly that PPRR is over 40bar$^{\circ}\text{CA}$ in moderate load and speeds between 1000rpm and 1200rpm as shown in figure 8c.

Especially, over 50bar$^{\circ}\text{CA}$ of PPRR, almost twice of maximum of PPRR at the altitude of 1000m, in the zone marked with red color locates in the 40% of maximum torque at 1200rpm. This means a strong pressure fluctuation occurs at this operation point.
4.4. Combustion characteristics at 40% of maximum torque and speed of 1200rpm

It is necessary to deeply analyze the combustion characteristic on this condition, with consideration of over rich mixture (excess air ratio<1.0) , worse combustion (BTE<15%) and severe pressure oscillation (PPRR>50bar/°CA) as shown in figure 6c and figure 3c. Analyses of cycle to cycle variation of peak pressure rise rate, pressure trace and knocking frequencies will be done at this operation point.

4.4.1. Effect on cycle to cycle variation of peak pressure rise rate. To achieve a deeper understanding the effect of altitudes on the peak pressure rise rate, cycle to cycle variations of PPRR were calculated by following parameters:

- mean value of PPRR

\[
\overline{PPRR} = \frac{1}{N} \sum_{i=1}^{N} PPRR_i
\]

(4)

where \(PPRR_i\) is the value of PPRR in the i-th cycle, and N is the total number of consecutive operation cycles (N=120) at the specific operation point.

- standard deviation of PPRR

\[
\delta_{PPRR} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (PPRR_i - \overline{PPRR})^2}
\]

(5)

Cycle to cycle variation of PPRR was calculated by \(\overline{PPRR}\) and \(\delta_{PPRR}\), as shown in equation (6),

\[
COV_{PPRR} = \delta_{PPRR}/\overline{PPRR} \times 100\%
\]

(6)
Figure 9 shows the cycle to cycle variation of PPRR calculated on the condition of the 40% of maximum torque at 1200rpm at three altitudes of 1000m, 3000m and 4500m, respectively. COV_{PPRR} equals to 21.2%, 22.8% and 25.4%, no big difference for cycle to cycle variation of PPRR alone can be found from figure 9. However, PPRR distributions of three cases differ widely in the mean value and standard deviation.

The blue inverted triangle scatters denote the PPRR in the single cycle, the red solid line denotes the mean value of PPRR, the cyan dash line denotes the sum of \( \mu_{PPRR} \) and \( \delta_{PPRR} \) and the magenta short dot line denotes the sum of \( \mu_{PPRR} \) and twice of \( \delta_{PPRR} \). At the altitudes of 1000m and 3000m \( \mu_{PPRR} \) equals to 24 and 28 bar/oCA, respectively. And \( \delta_{PPRR} \) equals to 5 and 6 bar/oCA, respectively, indicating a concentrated distribution of PPRR and good combustion stability. In detail, at the altitudes of 1000m PPRR in 66.7% of total cycles (80 among 120 cycles) concentrates on the range of 20 to 30 bar/oCA, and in only 2 cycles PPRR is over 40 bar/oCA as illustrated in figure 10a. Similarly, at the altitudes of 3000m PPRR in 64.2% of total cycles (77 among 120 cycles) concentrates on the range of 20 to 30 bar/oCA, and in only 4 cycles PPRR is over 40 bar/oCA as illustrated in figure 10b. While at the altitude of 4500m both mean value and standard deviation of PPRR are dramatically enhanced, that is, \( \mu_{PPRR} \) equals to 56 bar/oCA and \( \delta_{PPRR} \) equals to 14 bar/oCA, which are twice of those at the altitude of 3000m. PPRR in 91.7% of total cycles (110 among 120 cycles) is over 40 bar/oCA as illustrated in figure 10c, 55 times of that at the altitude of 1000m. Above all, associated with no damage of engine under the altitudes of 3000m, PPRR should be controlled under 50 bar/oCA.
4.4.2. Pressure trace analysis for the cycles of minimum and maximum of PPRR at the altitude of 4500m. In order to understand the effect of this big standard deviation of PPRR on the combustion at 40% maximum torque and speed of 1200rpm at the altitude of 4500m, figure 11 shows the comparison of in-cylinder pressures traces for the cycles of minimum and maximum of PPRR, that is, Cycle 41 and Cycle 85. A sharp pressure rising and then a strong pressure fluctuation can be observed around the top dead centre in Cycle 85, as comparing with a relatively smooth pressure curve of Cycle 41 as illustrated in figure 11. The pressure trace of Cycle 85 is similar with the typical super-knock pressure trace in boost SI engines adapted in figure 10 except the combustion phasing. This reveals the possibility of “diesel knock” with a comparable KI intensity of super-knock in SI engines.

Figure 10. Statistics of PPRR in individual cycles at various altitudes. (a)1000m, (b) 3000m, (c) 4500m.
The histogram of counting the cycles responding to partition of PPRRs with a resolution of 10 bar°CA.

Figure 11. Comparison of in-cylinder pressure in the minimum and maximum of PPRR at the altitude of 4500m. PPRRs in Cycle 41 (black solid line) and Cycle 85 (red solid line) equal to 30 and 103 bar°CA, respectively.
4.4.3. Knocking frequency analysis

According to the acoustic Draper’s “drum mode” theory [8], the first four modes of pressure oscillation in a cylindrical combustion chamber were considered in this study as listed in table 3. And the knocking frequencies are calculated by equation (1) with temperatures ranging from 2000K to 2500K and a constant specific heat ratio \( \gamma = 1.34 \) in this study.

Table 3. Acoustic modes of a cylindrical combustion chamber with T=2000~2500K.

| Mode(m,n) | 1,0 | 2,0 | 0,1 | 3,0 |
|-----------|-----|-----|-----|-----|
| Mode shapes | +− | +− | +− | +− |
| \( a_{m,n} \) | 1.84 | 3.054 | 3.832 | 4.201 |
| Mode # | 1 | 2 | 3 | 4 |
| \( f_{m,n}/kHz \) | [3.5, 3.9] | [5.8, 6.5] | [7.3, 8.1] | [8.0, 8.9] |

According to the acoustic theory described above, frequency-domain analyses are necessary for the multiple pressure oscillation modes resulted from the diesel knock confined in the combustion chamber. Figure 12 shows the power spectral density (PSD) obtained by fast Fourier transform (FFT) method of the cylinder pressures of Cycle 41 and Cycle 85 at 40% maximum torque and speed of 1200rpm at the altitude of 4500m. As illustrated in figure 12, the frequencies of the peaks in four oscillation modes are consistent well with the theoretical values in table 3 and the main resonance peak is around 3.9kHz (mode#1). By means of FFT spectrum analyses, the high-pass frequency for knock analysis can be determined. According to figure 12, a high-pass frequency of 3kHz is determined to eliminate the low-frequency pressure vibrations attributed by the piston reciprocating motion and normal combustion. The FFT and high-pass filtering of pressure traces were carried out on the platform of Origin™ software with the window function of rectangle.

Figure 12. PSD of the individual unfiltered pressure traces of Cycle 41 and Cycle 85. Mode#1, mode#2, mode#3 and mode#4 represent the frequency ranges of [3.5, 3.9], [5.8, 6.5], [7.3, 8.1] and [8.0, 8.9]kHz, respectively.

Thus, the knock intensity (KI) at 40% maximum torque and speed of 1200rpm can be obtained by means of the method described in figure 1. The correlation between PPRR and KI in individual cycles at various altitudes at his operation point was obtained. As illustrated in figure 13, the relationship between PPRR and KI shows correlation with a 73% goodness of fit. Besides, according to this correlation expression, KI control limit of 38 bar can be preliminarily estimated through PPRR limit of 50 bar/\(^{\circ}\)CA so as to ensure the engine durability.
5. Conclusions

Utilized by the plateau simulation test bench, combustion characteristics of a V6 heavy-duty intercooled-turbocharged diesel engine were investigated at various altitudes of 1000m, 3000m and 4500m. Studies of altitude on the brake thermal efficiency, excess air ratio, maximum combustion pressure and peak pressure rise rate, and cycle to cycle variation of peak pressure rise rate were made and the correlation of peak pressure rise rate and knock intensity was revealed. The major conclusions are drawn as follows.

1. Generally, the brake thermal efficiency enhances as the increase of load and speed at the same altitude. Almost 2% of reduction of the brake thermal efficiency on the conditions with speeds higher than 1300rpm with the altitude changing from 1000m to 3000m and from 3000m to 4500m.

2. Below 1.2 of excess air ratios worsen the combustion efficiencies at the operation points with the moderate and high loads and speeds below 1200rpm at the altitude of 4500m. The brake thermal efficiencies in those cases are 5% to 10% lower than those at the altitude of 3000m.

3. Maximum combustion pressure decreases with the increase of altitude generally due to the dilution of fresh charge. However, a dramatic variation of maximum combustion pressure in the moderate load and speeds between 1000rpm and 1200rpm at the altitudes of 3000m and 4500m.

4. Cycle-average peak pressure rise rates are lower than 32 bar/°CA at the altitudes of 1000m and 3000m. Over 50bar/°CA of cycle-average peak pressure rise rate are found at the 40% of maximum torque at 1200rpm. At this operation point the excess air ratio is below 1.0 and the brake thermal efficiency is lower than 15%. Above all, this operation point was selected for the deeper analyses of cycle to cycle variation of peak pressure rise rate and its correlation with knock intensity.

5. Although almost no big difference in the cycle to cycle variation of peak pressure rise rate, distributions of peak pressure rise rate in three cases differ widely in the mean value and standard deviation at the 40% of maximum torque at 1200rpm.

- In terms of mean values, they equal to 24 bar/°CA, 28 bar/°CA and 56 bar/°CA at the altitudes of 1000m, 3000m and 4500m, respectively.
- With regards to standard deviations, they equal to 5 bar/°CA, 6 bar/°CA and 14 bar/°CA at the altitudes of 1000m, 3000m and 4500m, respectively.
- As for individual distributions, numbers of cycles over 40 bar/°CA of peak pressure rise rate equal to 2 and 4 at the altitudes of 1000m and 3000m, respectively, and those equal to 110 at the altitude of 4500m, 55 times of that at the altitude of 1000m.

Figure 13. Correlation of PPRR and KI at various altitudes. Black scatters denote all the PPRRs of individual cycles at the altitudes of 1000m, 3000m and 4500m. Red solid line represents the correlation of PPRR and KI. That is, KI=0.77PPRR-0.26, and correlation coefficient equals to 0.73. PPRR limit = 50bar, and KI limit = 38 bar.
Almost all the peak pressure rise rates in individual cycles are lower than 50 bar°CA at the altitudes of 1000m and 3000m. Associated with no damage of engine under the altitudes of 3000m, peak pressure rise rate should be controlled under 50 bar°CA.

6. Knocking frequencies were predicted according to the classic acoustic theory, which achieve a good agreement with the FFT spectrum of the experimental cylinder pressure. By means of PSD analyses, the high-pass frequency for knock analysis can be determined and knock intensity was calculated. Thus, the correlation between KI and peak pressure rise rate was revealed through the linear regression method with a 0.73 of correlation coefficient at the 40% of maximum torque at 1200rpm. And knock intensity was preliminarily commented to be controlled under 38 bar to prevent from the piston erosion resulted from a high pressure rise rate.

In future, more work will be done on the strategy for the diesel knock control. Besides, the design of combustion system requires more work in the attenuation of knock.

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## Definitions/Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| ATDC         | After Top Dead Center |
| B            | Bore |
| BTE          | Brake Thermal Efficiency |
| CA           | Crank Angle |
| CI           | Compression-Ignition |
| COV          | Cycle-to-Cycle Variation |
| FFT          | Fast Fourier Transform |
| HCCI         | Homogeneous-Charge Compression-Ignition |
| HPF          | High-Pass Filtering |
| IMEP         | Indicated Mean Effective Pressure |
| KI           | Knock Intensity |
| LHV          | Low Heat Value |
| PCCI         | Premixed-Charge Compression-Ignition |
| PPC          | Partially Premixed Compression-Ignition |
| PPRR         | Peak Pressure Rise Rate |
| PSD          | Power Spectral Density |
| SI           | Spark-Ignition |