The interdependency between the maximal pressure and ion current in a spark-ignition engine

Zhongquan Gao1, Xiaomin Wu1, Zuohua Huang1, Sadami Yoshiyama2, Eiji Tomita3, Kazuki Yamazaki3 and Taro Higashi3

Abstract
An experimental investigation on the interdependency between the maximal pressure and ion current in a spark-ignition engine was conducted in this work. Eight ion current sensors were located centrally symmetric in a gasket between the cylinder and its head. The measurements of the ion current and the start timing, peak timing and end timing of the ion current were compared and the optimized interdependency between the maximal pressure and characteristic parameter of ion current was investigated. Experimental results show that the peak timing and the end timing of the ion current depend strongly on the start timing of the ion current for each ion sensor. The interdependency between the maximal pressure and start timing detected from the sensors near the intake port is better than that of the exhaust port. Furthermore, interdependency between the maximal pressure and average start timing from sensors 3 to 7 were found to give the best performance regardless the engine test conditions. The maximum pressure and average start timings were found to vary inversely with increasing intake pressure, ignition timing and excess air fuel ratio.

Keywords
Gasoline engine, ion current, combustion, maximal in-cylinder pressure, flame propagation

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Introduction
With increasing concern of fuel shortages and exhaust emissions, much effort has been concentrated on various spark-ignition (SI) engine electronic control techniques. Ionization current measurement is a new electronic control technique that is cost effective, convenient and which shows excellent response. Thus, much research work on ion current measurement has been conducted for misfire detection, knock detection, ignition timing advance control, air/fuel ratio estimation, pressure estimation and maximal pressure position estimation.1–10

The maximal pressure in the cylinder is one of the most important parameters to evaluate engine performance, and many characteristic parameters related to the combustion are usually chosen for better correlation of the maximal pressure.11–13 Litak et al.14 investigated the interdependency between cyclic peak pressure and peak pressure angle oscillations, and found that detailed analysis of the interdependency can provide further useful information on combustion dynamics. They also suggested that the rate of slow and/or fast individual burning phases are relevant to slow and fast heat release. Lee et al.15 utilized combustion parameters, such as indicated mean effective pressure (IMEP), mass fraction burned, heat release and combustion duration to evaluate the maximal pressure, and found a satisfactory relationship between the above parameters and the maximal pressure. However, the parameters are all calculated from the measured cylinder pressure data. Observing the flame propagation process is a good way to better understand the maximum pressure; however, its cost is very high, even unaffordable, for many researchers.16,17 Thus, it has become

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Recently, some researchers found that the ion current method using a spark plug as a sensor can conveniently evaluate parameters related to the maximal pressure. Wickstrom et al. estimated the peak pressure position (PPP) using the ion current method. Hellring and Holmberg investigated the estimation of in-cylinder PPP based on the ion current method, and established peak-finding algorithms for feedback of the PPP to an online controller. Rivara et al. used the ionization current as a signal to control the cylinder PPP, and they described a neural-network (NN)-based scheme for the control of PPP by spark timing in a gasoline internal combustion engine. However, the ion current is a local parameter around the electrodes, and the ion current signal is easily affected by air/fuel ratio, temperature and gas flow around the electrodes, which would affect the interdependency between the ion current and pressure parameters. Much effort has been made to better understand the factors that will influence the ion current. Franke et al. detected the ion current using a disc installed on the electrodes in a constant volume combustion vessel, and showed that a peak of the current appeared immediately after the flame passed the disc. Yoshiyama et al. found that the ion current was dominated by the contact area between the flame and the combustion chamber wall. Wu et al. used the ion current electrodes located at different positions in a constant volume bomb, and found that the contact between the flame and the wall is an important factor for the ion current waveform. From the above research, it is known that the contact between the flame and electrode is an important factor for the increase of ion current; therefore, some researchers installed ion current sensors at different locations to obtain more information on flame propagation, and they have established the relationship between ion current for different locations and pressure parameters.

Table 1. Engine specifications.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
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<tbody>
<tr>
<td>Bore (mm)</td>
<td>87.5</td>
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<tr>
<td>Stroke (mm)</td>
<td>83.1</td>
</tr>
<tr>
<td>Displacement (cc)</td>
<td>1998.8</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9.1</td>
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<tr>
<td>Fuel</td>
<td>gasoline</td>
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</table>

Additionally, Yoshiyama et al. designed multiple ion sensors to obtain the ion current in an SI engine, and found that the peak location of the ion current is close to the peak location of heat release calculated from the measured cylinder pressure under all engine operating modes. Furthermore, Badawy et al. presented experimental data and analysis of the ion current produced in a single-cylinder diesel engine equipped with an electronically controlled common-rail-injection system using an accessible engine control unit, and the correlation coefficients between combustion parameters and the ion current were investigated. However, further research is still needed to find a more accurate parameter for the pressure characteristic correlation.

In this study, the ionization current generated in an SI gasoline engine was measured using eight sensors in the cylinder head gasket. First, the interdependency between start timing and peak timing or end timing was investigated, in which the start timing was chosen as the evaluation parameter for maximal pressure of combustion. Second, the interdependency between the maximal pressure and start timings detected from different gasket ion sensors were analyzed. Finally, the average start timings for some gasket ion sensors were used to correlate the maximal pressure during the combustion for different operating conditions. This study is expected to introduce an optimized parameter of ion current for evaluation of maximal pressure and show appropriate positions for the installation of ion current sensors.

Experimental specifications

A four-cylinder SI engine fueled with gasoline is used in the study. The specifications of the test engine are listed in Table 1. Figure 1 shows a schematic diagram of the engine mounted with the ion current sensor. The intake pressure of fuel was controlled using a manometer in the supply system of the engine constituents, and the ignition timings and excess air ratio can be adjusted using an ECU Electronic control unit system. The in-cylinder pressure during combustion process was obtained using a piezoelectric absolute pressure transducer. The ion current measurement system was installed at one cylinder, while the signal of cylinder pressure, together with ion current signal data, were recorded using a Yokogawa data acquisition system. The experiments were conducted at an engine speed of 1500 r/min, and the signal of pressure and ion current were acquired for every 0.5° crank angle (CA). The pressure and ion current of 68 consecutive cycles of each stable operating condition were recorded to analyze the interdependency between pressure and ion current.

The ion sensor and ion current measuring circuit assembly is shown in Figure 2. Figure 2(a) shows the longitudinal section of the cylinder and gasket ion sensor. The ion sensor was connected to DC power (12 V) and a resistor R (100 kΩ). Figure 2(b) shows the
horizontal cross-section of the gasket, together with the shape of the eight ion sensors. It is seen that eight metal ion sensors of the same size are symmetrically installed around the cylinder, and that the cyclic arrangement of the eight ion sensors ensures that ion current can be detected from all directions in the cylinder. In addition, ‘EX’ and ‘IN’ in Figure 2(b) represent the exhaust valve and intake valve, respectively. Figure 2(c) shows the geometrical size of the ion sensors and head gasket. The total thickness of the head gasket is 2 mm, and the thickness of the electrode and insulator in the head gasket are 1.6 mm and 0.4 mm, respectively.

The mechanism of the ion current is that of an electrical field provided by the DC power: many of the charged particles generated during the combustion process will move in a fixed direction, and then a current called the ‘ion current’ is generated and can be obtained from the resister. To correlate the characteristic parameters of ion current and pressure, the correlation coefficient (R), which can reflect the interdependency between any two variables is used. R can be calculated from:

\[
\begin{align*}
\bar{x} & = \frac{1}{N} \sum_{i=1}^{N} x_i \\
\bar{y} & = \frac{1}{N} \sum_{i=1}^{N} y_i \\
SD_x & = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \\
SD_y & = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y})^2} \\
R(x, y) & = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y})/(SD_x \cdot SD_y)
\end{align*}
\]

where \(x_i\) and \(y_i\) represent the specific values of the samples x and y in a combustion cycle. N is the total number of the cycles. \(\bar{x}\) and \(\bar{y}\) are the average values, \(SD_x\) and \(SD_y\) are the standard deviations. The interdependency between samples x and y is evaluated by the coefficient R.

**Experimental results**

Figure 3 shows typical waveforms of the ion current obtained from multiple ion sensors, the sum of the ion current for eight gasket sensors, pressure and heat release. The heat release was calculated on the basis of pressure from an individual cycle with a Matlab computer data processing program. It is well known that radical ions, such as \(\text{CH}_3^+\), \(\text{CHO}^+\), \(\text{C}_2\text{H}_3^+\) and \(\text{H}_3\text{O}^+\), are produced by chemical reactions in the propagating flame zone, and the dominant ion is \(\text{H}_2\text{O}^+\). The principal mechanism can be illustrated as follows:

\[
\text{CH} + \text{O} \rightarrow \text{CHO}^+ + e^-, \text{the subsequent charge transfer}
\]

\[
\text{CHO}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{CO}
\]

The flame propagates from the ignition center to the cylinder wall, thus, ion current occurs immediately after the flame arrives at the ion current sensor, and the sharp increase of ion current is defined as \(\theta_{\text{start}}\), as shown in Figure 3(a). With the increase of contact area between...
the flame and the wall, the ion current increases to a maximum value, and then the current decreases until the combustion is finished. The peak current location is defined as $u_{\text{peak}}$, and the location where the ion current vanishes is defined as $u_{\text{end}}$ in Figure 3(a). The three timings of each ion current include information about the contact between the flame and the cylinder wall. Figure 3(b) shows the sum of the eight ion currents, the heat release and the pressure profiles. It is seen that the peak location of the three parameters are different, i.e. the maximum ion current sum occurs at 25° CA after top dead center (ATDC), the peak heat release occurs at 15° CA ATDC, and the maximal pressure is at 25° CA ATDC.

Figure 4 shows the $u_{\text{start}}$, $u_{\text{peak}}$ and $u_{\text{end}}$ for eight gasket sensors in a radar form. The eight coordinates are the CA, and the three timings for the eight gasket sensors form three closed curves; thus, the flame propagation information around the eight sensors can be easily compared. From Figure 4, it can be seen that the profiles of the three closed curves are similar; this reflects that the $u_{\text{start}}$, $u_{\text{peak}}$ and $u_{\text{end}}$ are relevant to each other.

The other information is that the eight $u_{\text{start}}$, $u_{\text{peak}}$ and $u_{\text{end}}$ values are not equal, which shows that the propagation of flame is not symmetrical in the eight directions.

**Relationships between the three timings of the ion current**

Due to the complex combustion mechanism, even under the same operating condition, the ion currents are different cycle by cycle. Figure 5 illustrates the eight $u_{\text{start}}$, $u_{\text{peak}}$ and $u_{\text{end}}$ values for 68 cycles under the same operating conditions as that in Figure 3. Although the three timings vary cycle by cycle, the trend of the three curves for each sensor are similar; additionally, the shape of three closed curves in Figure 4 are similar, and so the interdependencies between $u_{\text{start}}$, $u_{\text{peak}}$ and $u_{\text{end}}$ are investigated.

Figure 6(a) shows $u_{\text{peak}}$ and $u_{\text{end}}$ versus $u_{\text{start}}$, and the calculated $R(\theta_{\text{start}}, \theta_{\text{peak}})$, $R(\theta_{\text{start}}, \theta_{\text{end}})$ at eight sensors. It is seen that the correlation coefficient is larger than 0.7 for nearly all of the sensors. Generally, it is
acceptable that the correlation coefficient is higher than 0.65. This indicates that $u_{\text{peak}}$ and $u_{\text{end}}$ are strongly dependent on $u_{\text{start}}$. In addition, $u_{\text{start}}$ is obvious and easily discriminated from the perspective of electronic control. Furthermore, it is known that the flame speed is related to pressure. Thus, the $u_{\text{start}}$ information is selected for the interpretation of the interdependency between $u_{\text{start}}$ and maximal pressure in this paper.

**Evaluation parameters for maximal pressure**

Since maximal pressure ($p_{\text{max}}$) in the cylinder during combustion is an important parameter for depiction of the output of the engine, researchers have utilized many parameters to correlate $p_{\text{max}}$, such as corresponding CA for maximal pressure ($\theta_{p_{\text{max}}}$) and IMEP. At the same operation conditions as in Figure 3, $p_{\text{max}}$ also shows better relationships with $\theta_{p_{\text{max}}}$ and IMEP in this experiment, as seen in Figure 7, where $R(\text{IMEP}, \theta_{p_{\text{max}}})$ and $R(p_{\text{max}}, \theta_{p_{\text{max}}})$ are 0.93 and 0.9, respectively.

However, $\theta_{p_{\text{max}}}$ and IMEP are based on pressure data, and are limited in use due to the high cost of pressure sensors. To establish a better relationship between $p_{\text{max}}$ and the characteristic parameters of the ion current, Figure 8 shows the interdependency between $\theta_{\text{start}}$ and $p_{\text{max}}$ for the eight gasket sensors.

It is seen that interdependencies between the $p_{\text{max}}$ and $\theta_{\text{start}}$ for the eight gaskets sensors are different. The reason is that pressure is an average parameter, while ion current is a local parameter, and the flame propagation pattern in the cylinder is asymmetrical. The relationship between $p_{\text{max}}$ and $\theta_{\text{start}}$ represents the correlation between the average parameters and the local parameters; thus, $R(p_{\text{max}}, \theta_{\text{start}})$ for different gaskets needs to be compared. It is seen that $R(p_{\text{max}}, \theta_{\text{start}})$ for gasket 5 and gasket 6 are larger than $R(p_{\text{max}}, \theta_{\text{start}})$ for other gaskets. It is known that the temperature at the intake valve side is lower than the temperature at the exhaust valve side and the probability of knock is less near the intake valve than that around the exhaust valve; thus, the flame at the intake valve side is more steady than that at the exhaust valve side. For the same reason, $R(p_{\text{max}}, \theta_{\text{start}})$ for gaskets 1, 2 and 8 located around the exhaust valve side are weak. Although $R(p_{\text{max}}, \theta_{\text{start}})$ for some gasket ion sensors seems large, it is not good enough for the practical application of the ion current method.
Figure 5. $\theta_{\text{start}}$, $\theta_{\text{peak}}$ and $\theta_{\text{end}}$ for eight gaskets.

Figure 6. Interdependency between $\theta_{\text{peak}}$, $\theta_{\text{end}}$ and $\theta_{\text{start}}$. 
Relationship between the average start timing of the ion current and $p_{\text{max}}$

To exclude the local limitation of $\theta_{\text{start}}$ for a single gasket and find an appropriate parameter to correlate with $p_{\text{max}}$, average $\theta_{\text{start}}$ (average start timing (AS)) of ion current for different gasket ion sensors were adopted, and the correlation coefficient between $p_{\text{max}}$ and AS $R(\text{AS}, p_{\text{max}})$ was analyzed, as shown in Figure 9, where (m.n.k) after AS means gasket sensor m, n and k, while (m-n) after AS means from gasket sensor m to gasket sensor n.

Figure 9 shows that $R(\text{AS}(1.2), p_{\text{max}})$ is larger than the interdependency between $\theta_{\text{start}}$ for the single gasket 1 or gasket 2 and $p_{\text{max}}$ in Figure 8, respectively. $R(\text{AS}(5.6), p_{\text{max}})$ in Figure 9 is also larger than the interdependency between the pressure and $\theta_{\text{start}}$ for the single gasket 5 or gasket 6 in Figure 8, respectively. Since $R(\text{AS}(5.6), p_{\text{max}})$ is larger than $R(\text{AS}(1.2), p_{\text{max}})$, AS(5.6) is chosen for analysis. In Figure 9, $R(\text{AS}(4.6), p_{\text{max}})$ is larger than $R(\text{AS}(5.6), p_{\text{max}})$, $R(\text{AS}(4.7), p_{\text{max}})$ is similar to $R(\text{AS}(3.6), p_{\text{max}})$, both are larger than $R(\text{AS}(4.6), p_{\text{max}})$, and $R(\text{AS}(3.7), p_{\text{max}})$ is larger than $R(\text{AS}(4.7), p_{\text{max}})$. This indicates that $R(\text{AS}, p_{\text{max}})$ increases with the number of gasket sensors. However, $R(\text{AS}(3.8), p_{\text{max}})$ is smaller than $R(\text{AS}(3.7), p_{\text{max}})$, and $R(\text{AS}(1.8), p_{\text{max}})$ is also smaller than $R(\text{AS}(3.7), p_{\text{max}})$. $R(\text{AS}, p_{\text{max}})$ decreases with the number of gasket sensors when the number of gasket sensors is larger than

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**Figure 7.** Interdependency between $p_{\text{max}}$ and IMEP and $\theta_{\text{pmax}}$

**Figure 8.** Interdependency between $\theta_{\text{start}}$ and $p_{\text{max}}$. 

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five. This indicates that AS(3-7) is the best parameter for evaluation of $p_{\text{max}}$.

To confirm the best gasket sensors, $R(\text{AS}, p_{\text{max}})$ for different gasket ion sensors is compared with $R(\text{AS}(3-7), p_{\text{max}})$. Figure 10 shows $R(\text{AS}, p_{\text{max}})$ for some gasket ion sensors with irregular order.

With the same number of gasket ion sensors, $R(\text{AS}, p_{\text{max}})$ for gasket sensors including gasket 5 and 6 is large, while $R(\text{AS}, p_{\text{max}})$ for gasket sensors including gasket 8 is small. This confirms that $\theta_{\text{start}}$ for gasket sensors around the intake valve side are better for the evaluation of $p_{\text{max}}$. For all cases in Figure 10, $R(\theta_{\text{start}}, p_{\text{max}})$ for AS(3-7) is also largest. This indicates that the best evaluation parameter for $p_{\text{max}}$ is AS(3-7). Figure 11 gives AS(3-7) and $p_{\text{max}}$ for 68 cycles. The axis of the $\theta_{\text{start}}$ was inverted in Figure 11, as AS(3-7) is in contrast with flame speed. It can been seen in Figure 11 that $\theta_{\text{start}}$ was related with flame speed. It can been seen in Figure 11 that AS(3-7) shows similar trends with $p_{\text{max}}$ for the 68 cycles. This indicates that $p_{\text{max}}$ is related to flame propagation with the same operating conditions. Therefore, AS(3-7) is chosen for the evaluation of $p_{\text{max}}$ in this paper.

**The combustion diagnostic using the ion current**

In practice, engine operating conditions, such as ignition timing, air/fuel ratio and intake pressure, vary, and operating condition is an important influencing factors on $p_{\text{max}}$; thus, it is necessary to study the relationship between $p_{\text{max}}$ and AS(3-7) for different operating conditions.

Figure 12 illustrates the relationship between $p_{\text{max}}$ and AS(3-7) at different ignition timings. The operating condition is that the excess air ratio ($\lambda$) is 0.8, and the intake pressure is 80 kPa.

The results show that $R(\text{AS}(3-7), p_{\text{max}})$ is larger than 0.93 at all ignition timings. This confirms that $p_{\text{max}}$ is strongly dependent on the average flame development near gasket sensor 3 to gasket sensor 7. Figure 12 also shows that the advancement of the ignition timing increases the $p_{\text{max}}$ and decreases AS(3-7). This indicates the satisfactory relationship between flame propagation and maximal pressure.

Figure 13 shows the relationship between $p_{\text{max}}$ and AS(3-7) at different intake pressures, which varied from 70 kPa to 100 kPa. The operating condition is that $\lambda = 1.0$ and ignition timing is 25° CA before top dead center (BTDC). Good interdependency between $p_{\text{max}}$ and AS(3-7) is present for different intake pressures. This indicates that $p_{\text{max}}$ values are strongly dependent on the AS(3-7). Figure 14 shows AS(3-7) and $p_{\text{max}}$ versus intake pressure. It can be seen that the increase of intake pressure increases $p_{\text{max}}$ and decreases AS(3-7). This suggests that faster flame propagation results in higher maximal pressure.
Figure 10. Interdependency between AS and $p_{\text{max}}$.

Figure 11. AS(3-7) and $p_{\text{max}}$ for 68 cycles.

Figure 15 shows the interdependency between $p_{\text{max}}$ and AS(3-7) at different $\lambda$, and the value of AS(3-7) and the $p_{\text{max}}$ versus $\lambda$. The operating condition is that ignition timing is 25°CA BTDC. It can be seen that the interdependency between the AS(3-7) and the $p_{\text{max}}$ are satisfactory. In addition, with the increase of $\lambda$, $p_{\text{max}}$ first increases and then decreases, and the largest $p_{\text{max}}$ is present, while AS(3-7) decreases initially and then increases. The obvious inverse trend between $p_{\text{max}}$ and AS(3-7) indicates that a high flame speed corresponds to a high maximal pressure.

Conclusions

Ion current generated during combustion in an SI gasoline engine was obtained from eight gasket ion sensors installed in the cylinder gasket. The interdependency between the characteristics of ion signals and maximal pressure were analyzed under various experimental conditions (0.8 ≤ excess air fuel ratio ≤ 1.2, 10° ≤ ignition timing ≤ 30°CA BTDC, 70 ≤ intake pressure ≤ 100 kPa). The main results are summarized as follows.

1. For all gasket sensors, the peak timing and end timing of the ion current are strongly dependent on the start timing of the ion current.
2. Interdependency between the start timing of the ion current for gasket sensors near intake valves and maximal pressure is strong, while interdependency between the start timing of the ion current for gasket sensors near the exhaust valve and maximal pressure is weak.
3. Interdependency between average start timings of the ion current from gasket sensor 3 to gasket sensor 7 and maximal pressure is optimum at all operating conditions in this paper.
4. The intake pressure, the ignition timing and equivalence ratio show large effects on maximal pressure.
Figure 12. Relationship between AS(3-7) and $p_{\text{max}}$ at different ignition timings.

Figure 13. $R(\text{AS}(3-7), p_{\text{max}})$ for different intake pressures.
and average start timing, and the maximal pressure shows an inverse trend with average start timing.

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Acknowledgements
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References
9. Dee J, Kujawski D and Tuzinkewich J. System for producing product gas used in e.g. diesel engine comprises electric current applied to anode/cathode plates of electrolytic cell to generate the gas by dissociating...


### Appendix I

**Notation**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>( n )</td>
<td>engine speed</td>
<td>( r/\text{min} )</td>
</tr>
<tr>
<td>( N )</td>
<td>total number of cycles</td>
<td></td>
</tr>
<tr>
<td>( p_{\text{max}} )</td>
<td>maximal pressure</td>
<td>( \text{MPa} )</td>
</tr>
<tr>
<td>( R(x, y) )</td>
<td>correlation coefficient between variable ( x ) and ( y )</td>
<td></td>
</tr>
<tr>
<td>( \lambda )</td>
<td>excess-air ratio</td>
<td></td>
</tr>
<tr>
<td>( \theta_{\text{end}} )</td>
<td>timing when ion current disappears</td>
<td>( ^\circ \text{crank angle} )</td>
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<table>
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<td>( \theta_{\text{peak}} )</td>
<td>timing for peak value of ion current</td>
</tr>
<tr>
<td>( \theta_{\text{start}} )</td>
<td>timing when ion current appears</td>
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### Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AS</td>
<td>average start timing for some gasket ion sensors</td>
</tr>
<tr>
<td>ATDC</td>
<td>after top dead center</td>
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<td>BTDC</td>
<td>before top dead center</td>
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<td>CA</td>
<td>crank angle</td>
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<td>IMEP</td>
<td>indicated mean effective pressure (kPa)</td>
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<td>PPP</td>
<td>peak pressure position</td>
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