Combustion Characteristics Detection for Low Pressure Direct Injection Engines Using Ionization Signal

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ABSTRACT

It is well-known that in-cylinder ionization signals can be used for detecting combustion characteristics of IC (Internal Combustion) engines. For example, engine misfire, incomplete combustion (or partial-burn), knock, MBT (Minimum spark advance for Best Torque) timing and combustion stability can be detected using in-cylinder ionization signals. In addition, closed loop combustion spark timing control strategies have been developed to control engine MBT timing and to manage spark timing advance (knock) and retard (incomplete combustion) limits. In-cylinder ionization signals can also be used for closed loop control of maximum equivalence ratio (lean limit) at a desired combustion stability level. Up to now, most of the ionization applications have been for PFI (Port Fuel Injection) engines. This paper presents ionization detection for gasoline Direct Injection (DI) engines. The test data was obtained using a single cylinder engine equipped with Visteon’s LPDI (Low Pressure Direct Injection) system. The test data shows that the ionization signals can be used not only for detecting gasoline DI engine misfire, incomplete combustion, and MBT timing of gasoline DI engines similar to that of the PFI engines, but also for detecting a wet spark plug tip due to late fuel injection timing. Besides similar closed loop combustion control strategies (spark timing and maximum equivalence ratio) to the PFI case, the ionization signals can also be used for fuel injection timing control of gasoline DI engines.

INTRODUCTION

In-cylinder ionization signals have recently gained a lot of attention for combustion characteristic detection and its control. An example of a 300-cycle averaged ionization signal of a PFI engine is shown in Figure 1. It usually consists of two peaks following the ignition pulse. The first peak represents the flame kernel growth and development around spark plug (chemical ionization), and the second peak is the re-ionization (thermal ionization) due to the in-cylinder temperature increase as a result of both pressure increase and flame development in the cylinder. The thermal ionization may disappear at operating conditions with light loads or high EGR (Exhaust Gas Recirculation) rates. Nevertheless, an ionization signal provides a detailed fingerprint of the in-cylinder combustion process. It shows when a flame kernel is formed and propagates away from the spark plug gap, when the combustion is accelerating rapidly, when the combustion reaches its peak burn rate, and when combustion ends. Ionization signals have already been used to: correlate with in-cylinder pressure signal [1,2] in the sense of Mass Fraction Burned (MBF) location, predict Air-to-Fuel Ratio (AFR) ratio [3], detect engine misfire and knock [4,5], and to detect MBT timing and control it closed loop [6]. Ionization signals have also been utilized for closed loop knock and incomplete combustion (partial-burn) limit controls in a stochastic control framework with experimental verifications [7, 8].

![Figure 1: A typical cycle-average ionization signal](image-url)
similar to the PFI engines, but also for detecting a wet spark plug tip due to late injection timing during the compression stroke. Beside the similar closed loop combustion control strategies (spark timing and maximum equivalence ratio) to the PFI case, the ionization signals may also be used for fuel injection timing control of gasoline DI engines.

The test data shown in this paper was obtained using a three-valve 0.675L single cylinder engine equipped with Visteon's Low Pressure Direct Injection (LPDI) system [9, 10] and an ionization detection system, see Figure 2. The rail pressure of the LPDI fuel system is operated at around 20 bar. The ionization detection system used for the test is an ionization detection ignition coil with integrated electronics and coil driver. The integrated coil is a coil-on-plug design. The cylinder head was instrumented with a laboratory grade pressure sensor. The single cylinder engine was controlled by the engine dynamometer controller for spark and fuel injection. In-cylinder pressure and ionization signals were collected using a dynamometer data sampling system. For each test point, 300 cycles of test data was collected at one crank degree resolution. In the rest of paper, the ionization signals used are averaged over 300 cycles, or otherwise specified.

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In remaining sections of the paper we examine: engine incomplete combustion detection, engine MBT timing detection, combustion stability detection, and wet spark plug tip detection due to late second split injection. A concluding discussion follows.

INCOMPLETE COMBUSTION DETECTION FOR LPDI ENGINES

Incomplete combustion (or partial-burn) is an adverse combustion characteristic between a normal combustion event and misfire. Normally, when there is an incomplete combustion event, the combustion starts slowly after the spark event and may not be completed until the exhaust valve is open. Incomplete combustion and misfire detections are important features for gasoline engine controls. Using an ionization signal for misfire detection is a straightforward task since there is no ionization signal after the spark pulse if the engine misfires, while incomplete combustion detection is relatively difficult. Normally, incomplete combustion can be observed clearly using the P-V diagram of an in-cylinder pressure signal.

In reference [5], it has been shown that engine incomplete combustion (partial-burn) can be detected using an in-cylinder ionization signal. Figure 3 shows an incomplete combustion detection case for the gasoline DI engine using an in-cylinder ionization signal. The engine is operated at 1500 RPM with 5 bar IMEP (Indicated Mean Effective Pressure) load. Figure 3 shows in-cylinder pressure (gray lines) and ionization (black lines) signals for both normal and incomplete combustion, where the dash lines represent normal combustion and solid lines represent incomplete combustion. Both signals are single cycle signals. A normal combustion ionization signal has two peaks, while for incomplete combustion, the ionization signal is irregular; see the solid ionization line in Figure 3.

In remaining sections of the paper we examine: engine incomplete combustion detection, engine MBT timing detection, combustion stability detection, and wet spark plug tip detection due to late second split injection. A concluding discussion follows.

Figure 2: Test Setup

Figure 3: Partial-burn ionization signal

Figure 4 shows the corresponding P-V diagram of the in-cylinder pressure signals from both normal and incomplete combustion cycles, where the gray dash line is the P-V trace for the normal combustion cycle and solid black line is for the incomplete combustion case. It is clear that both pressure and ionization signals show incomplete combustion. In other words, for incomplete combustion detection, both ionization and pressure signals correlate well.
MBT TIMING DETECTION FOR GASOLINE DI ENGINES

The combustion process of an internal combustion engine is usually described using the mass fraction burned versus crank angle. Through mass fraction burned, one can find when the combustion has its peak burning velocity, acceleration and percentage burn location as a function of crank angle. Maintaining these critical events at a specific crank angle produces the most efficient combustion process. In other words, MBT timing can be found through these critical events. As described in [6], for PFI engines, the inflection point right after the first peak, called the first inflection point in [6] (see Figure 5 for 300 cycle averaged pressure and ionization signals), can be correlated to the maximum acceleration point of the net pressure and this point is usually between 10% to 15% mass fraction burned. The inflection point right before the second peak of the ionization signal (called the second inflection point in [6]) see Figure 5, correlates well with the maximum heat release point and occurs around the 50% mass fraction burned location. In addition, the second peak location is related to the peak pressure location of the pressure signal (see both Figure 1 and Figure 5).

As also described in references [11, 12], at MBT timing, the maximum acceleration point of mass fraction burned is located at around TDC; the 50 percent MFB location is between 8° and 10° after TDC; and the Peak Cylinder Pressure (PCP) location is around 15° after TDC. Using the MBT timing criteria relationship between in-cylinder pressure and the in-cylinder ionization signal, these three MBT timing criteria (maximum acceleration location of MFB, 50 percent MFB location, and PCP location) can be achieved using in-cylinder ionization signals for PFI engine spark control.

Figure 6 shows a 300 cycle average of both ionization and pressure signals when the single cylinder DI engine was operated at 1500 RPM with 5.0 bar IMEP load. Note that the main difference between PFI and LPDI engines is the mixing quality of air and fuel. For PFI engines, due to early air fuel mixing with the intake port, the mixture can usually be considered close to homogeneous, while for gasoline DI engines, due to direct injection during intake stroke, the air and fuel mixture is partially stratified. Due to the non-homogeneous air and fuel mixture, the combustion process is also quite different. Comparing Figure 1 and Figure 6 (300 cycle averaged signals), it can be observed that for PFI case, the second peak of the ionization signal is collocated with the peak of in-cylinder pressure signal, while for the LPDI case, there is an offset crank angle ($\Delta \theta$) between the second peak location of the ionization signal and peak location of the pressure signal. This is likely due to the differing
degrees of homogeneity in the air and fuel mixtures between the PFI and LPDI engines.

Figure 7 shows the ionization signal and the MFB curve calculated from the in-cylinder pressure signal (300 cycle average). The engine was operated at 1500 RPM with 5 bar load and 20 bar fuel rail pressure. From the vertical lines at 50% and 10% MFB locations, it is clear that for the gasoline DI engine, the 50% and 10% MBF locations are corresponding to the first valley and second peak of the 300 cycle averaged ionization signal (see Figure 7). Recall that for the PFI case, the 10% and 50% MFB locations are corresponding to the first and second inflection point locations. From the MFB curve shown in Figure 7, it can be observed that after the spark, the combustion starts relatively slowly compared to PFI case. It takes more time to burn 10% fuel, and therefore it also shifts the 10% and 50% MFB locations to the first valley and second peak location of the ionization signal.

Figure 8 and Figure 9 are used to study the correlation between MFB location and ionization signal characteristics. Figure 8 compares the 10% MFB location calculated from the in-cylinder pressure signal and the first valley location of the ionization signal and Figure 9 compares the 50% MFB location calculated from the in-cylinder pressure signal and the second peak location of the ionization signals. There are twelve test cases, defined in Table 1, and the data is presented in both Figure 8 and Figure 9. The twelve cases cover a range of engine operational conditions (fixed load with speed varying from 1500 to 2000 RPM) and also single and split injection. For split injection, the fuel is injected into the cylinder twice. The first injection occurs during the intake stroke, and second injection happens during the compression stroke.

From both Figure 8 and Figure 9, it can be seen that the 10% MFB location calculated from pressure signal corresponds well with the first valley location of the in-cylinder ionization signal, and that the 50% MFB location can be approximated by the second peak location of the ionization signal. Therefore, for the purpose of controlling engine MBT timing, one can use the second peak location as a measure of MBT timing. For instance, maintaining the 50% MFB location at around 9 degrees after TDC location insures that the engine is operated at its MBT timing, and one can also control the ionization signal second peak location around 9 degrees to achieve MBT timing.
Note that the MBT timing analysis is also based upon the data averaged over 300 cycles of ionization signal. For real-time implementation, a single cycle ionization signal should be used for estimating engine MBT timing. This approach has been validated in PFI applications, see [6], and we are confident that it can also be applied to DI applications. Although the MBT timing is correlated to ionization signals at a fixed load over a narrow speed range, we believe that it can be extended to all operational conditions for DI engines operated at nearly stoichiometric air-to-fuel ratio. This is mainly due to the fact that the technology has been proven for PFI engines and the ionization signals of DI and PFI engines are of the same order of magnitude.

COMBUSTION STABILITY DETECTION FOR LPDI ENGINES

Combustion stability is often measured by the COV (Coefficient Of Variance) of IMEP (Indicated Mean Effective Pressure). In general, a better combustion stability corresponds to a lower COV value. However, there is no direct method to obtain the COV of IMEP for an operating condition without an in-cylinder pressure sensor. Therefore, the closed loop control of maximum equivalence ratio (lean limit), idle spark timing, or any other combustion stability related engine control, is challenging in the absence of an in-cylinder pressure measurement. Without having an online measurement, all combustion related calibrations are pre-set for the engine family during the calibration process and remain fixed for the engine’s lifetime.

For an SI (Spark Ignition) engine, when the combustion stability is beyond the desired stability limit, the crank angle for the combustion to reach a certain fraction of fuel burned or for the combustion to complete usually becomes larger compared to a normal combustion event. The standard deviations for the corresponding angles also become larger [13]. Furthermore, both the initial flame development (0 to 5% burned) and main combustion durations (10% to 90% burned) increase when maximum equivalence ratio is approached (see [14], among others). Therefore, the COV of IMEP is not the only indicator of combustion stability for an SI engine, the duration of the combustion process in terms of crank angle degrees could also be an alternative indicator as well. However, the burn duration calculation still relies on an in-cylinder pressure measurement.

Ionization signals are closely related to the combustion process. Although their magnitude depends on combustion mixture contents, spark plug type, and the details of associated electronics, its basic shape is an indicator of the current combustion operating condition. A good or stable combustion requires events to occur at specific locations in the crank angle domain. An unstable combustion will result in an irregular ionization signal, delayed flame formation and delayed propagation. However, due to spark plug gap, fuel type, and engine to engine variations, ionization signals change magnitude and the changes could be significant at conditions where combustion stability is approaching the stability limit. Using the ionization magnitudes to define the combustion state would necessitate a tremendous calibration effort. In order to improve the robustness of the detection algorithm, one needs to rely on the shape of the ionization signal instead of the absolute value of the signal. One such shape based criteria is the Integration Distribution Location (IDL) illustrated in Figure 10, where the ionization signal shown is averaged over 300 cycles. Considering the integration window starting after the spark event, the IDL is defined as the crank angle from start of integration to a specific percentage of the integration value, such as 90%, is reached over the given integration window for the ionization signal. From a statistical analysis of the distribution function associated with the IDL’s, using single combustion cycle ionization signals, a measure of combustion stability may be obtained. The COV of the
IDL distribution gives an indication of the level of combustion stability much like the COV of the IMEP [7]. This approach to obtaining a measure of combustion stability may be extended to fuel injection timing.

Fuel injection timing for IC engines equipped with DI fuel systems is one of the key factors in controlling the combustion process. It affects IC engine emissions, fuel economy, combustion stability, etc. Figure 11 shows the COV plots of both IMEP calculated from the in-cylinder pressure signal and IDL calculated from the in-cylinder ionization signal (using a single cycle ionization signal) as a function of fuel injection timing. The engine was operated at 3000 RPM with 3.8 bar IMEP load. The parameter used for calculating the IDL is defined in Table 2.

The COV of IDL is calculated using the normalized IDL with mean value equals to one. The COV value displayed in Figure 11 is the percentage covariance obtained by multiplying one hundred to the calculated COV. Comparing with the covariance from in-cylinder pressure signal (top plot of Figure 11), the normalized COV calculated from ionization IDL has a very similar shape to in-cylinder pressure covariance. For example, minimum COV is achieved at injection timing 340 degrees before TDC. This makes it possible to optimize injection timing using ionization signals.

### Table 2: IDL calculation parameters

<table>
<thead>
<tr>
<th>Integration window width</th>
<th>Integration level</th>
</tr>
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<tbody>
<tr>
<td>120 crank degrees</td>
<td>20%</td>
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Figure 12 shows comparisons of both ionization and pressure signals (300-cycle averaged) when the engine was operated with a single injection or a split injection fuel strategy. The engine was operated at 1500 RPM with 5 bar IMEP load for both single and split injection cases, the fuel rail pressure was 20 bar and the spark timing was 30 degrees before TDC. The top two plots of Figure 12 show the injection timing, and the bottom plot shows the comparisons of the pressure and ionization signals between both single and split injection cases. It may be observed that the split injection case has higher peak cylinder pressure than the single injection case due to a partially stratified combustion. A significant difference between the two ionization signals may also be observed. From Figure 12, one can see that the height ratio of the second and first peaks is quite different. For single injection, the second peak is lower than the first peak, and for split injection, the situation is reversed.

### SPLIT FUEL INJECTION IONIZATION SIGNAL CHARACTERISTICS

Split injection strategies have been used in production DI engines. With split injection (one during the intake stroke and the other during the compression stroke), smooth torque output can be realized without smoke during light to heavy load transition due to a semi-stratified charge [15]. Split injection can also be used to suppress cylinder knock and reduce soot emissions at low engine speed, and to increase exhaust temperature during cold-start for quick warm up of the three-way catalyst [16].
Due to the light stratification for split injection, combustion for split injection completes faster than the single injection case. Figure 13 shows that the 90% MFB crank angle for split injection case is one crank degree ahead of the single injection case. This fact can also be observed from the in-cylinder ionization signal, post second peak, see Figure 12. One can see that the ionization signal of split injection dies out quicker than that of single injection. This faster combustion is also indicated in the calculated IDL values shown in Table 3. The IDL values shown in Table 3 are calculated using 120 crank degree integration window with 95% distribution. The IDL for split injection is 52 crank degrees and IDL for single injection is 54 crank degrees. This indicates that the combustion of split injection completes earlier than single injection.

Table 3: IDL for single and split injections

<table>
<thead>
<tr>
<th>Single Injection</th>
<th>Split Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>54 crank degrees</td>
<td>52 crank degrees</td>
</tr>
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</table>

One of the key control factors of split fuel injection is the second injection timing (in compression stroke). Since the purpose of the second injection is to obtain partially stratified combustion, both second injection timing and duration affect the quality of the stratified air-to-fuel mixture. When the end of second injection timing is close to TDC, the injected fuel could cause a wet spark plug due to upward movement of the piston. This may lead to misfire or partial-burn. The next paragraphs illustrate that ionization signals can be used to detect a wet spark plug condition and, hence, it can also be used to optimize the second injection timing as a feedback signal.

Figure 14 shows the ionization signals with both dry and wet spark plugs (300-cycle averaged signals). The engine was operated at 1500 RPM with 5 bars IMEP load, where the spark timing was fixed at 30 degrees. Split fuel injection is employed, where the EOI (End of Injection) of the first injection was fixed at 300 degrees before TDC, and the second injection EOI was at 70 and 65 degrees before TDC, respectively. The fuel mass fraction of split injection is 60% for the first injection and 40% for the second. The fuel rail pressure was set at 20 bar. The difference between the ionization signals in Figure 14 shows a distinguishing characteristic. The solid line shows a normal ionization signal with second injection EOI at 70 degrees before TDC, and the solid-dot line shows an abnormal ionization signal with second injection EOI at 65 degrees before TDC, where signal baseline is above zero (at around 0.3 volt which is equivalent to around 20 micro ampere ionization current). The increased baseline ionization current is mainly due to the wet spark plug caused by late second injection.
Figure 15 shows a single cycle ionization signal transition between dry and wet spark plugs. The engine was operated at the same conditions (speed, load, spark timing, and fuel mass fraction of the first and second injections) as Figure 14. The only difference is the fuel rail pressure and the second injection timing. The fuel rail pressure for this case was raised to 30 bars and second injection EOI timing for the wet plug case was 50° before TDC. A wet plug is mainly caused by late second injection. For the wet plug case, the injection starts at roughly 65° before TDC and ends at 50° before TDC. It takes some time for the fuel to travel to the spark plug, and that is why no ionization offset is observed in Figure 15. During the combustion process, the hot burned gas mixture dries the wet plug locally around spark plug gap, leading to a low ionization current around 50° after TDC. As the expansion continues, the wet fuel around spark plug tip penetrates to the spark plug gap and reduces the resistance in the spark plug gap, causing a gradual ionization current increase after combustion. Therefore, after combustion an ionization signal can be used for detecting wet spark plug due to late second injection.

CONCLUSION

This paper demonstrates that an in-cylinder ionization signal can be used to detect misfire and incomplete combustion (or partial-burn), to calculate MBT timing and obtain a combustion stability measure for a low pressure DI engine. Although these capabilities are shown at a fixed load over a narrow speed range, we are confident that it can be extended to a complete engine operational map similar to that of the PFI case.

For DI split fuel injection case, ionization signals can be used not only to distinguish the combustion difference between single and split injection but also to detect wet spark plug electrodes due to late split injection.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR: Air-to-Fuel Ratio
BTDC: Before Top Dead Center
COV: Coefficient Of Variance
DI: Direct Injection
IC: Internal Combustion
IDL: Integration Distribution Location
IMEP: Indicated Mean Effective Pressure
EGR: Exhaust Gas Recirculation
EOI: End of Injection
LPDI: Low Pressure Direct Injection
MBT: Minimum spark advance for Best Torque
MFB: Mass Fraction Burned
PCP: Peak Cylinder Pressure
PDF: Probability Density Function
PFI: Port Fuel Injection
P-V: Pressure-Volume
RPM: Revolution per Minute
SI: Spark Ignited
ST: Spark Timing
TDC: Top Dead Center