Investigation on characteristics of ionization current in a spark-ignition engine fueled with natural gas–hydrogen blends with BSS de-noising method

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A B S T R A C T

Investigation on ionization current characteristic in a spark-ignition engine fueled with natural gas, natural gas–hydrogen blends and gasoline was conducted. Blind Source Separation (BSS) de-noising method is employed to separate the ionization current signal from the interference of spark tail generated by ignition discharge. Cylinder pressure was recorded, and local temperature at spark plug gap is calculated using AVL-FIRE simulation code. Results show that the simulated cylinder pressures are in good agreement with those of measured and the spark tail and ionization current can be separated using BSS method. Front flame stage and post flame stage in ionization current can be used to analyze the combustion characteristics of natural gas–hydrogen blends. De-noised current shows that the appearance of front flame stage and post flame stage (including the peaks in the stages) fueled with natural gas is postponed and compared with that fueled with gasoline, and the appearance of front flame stage and post flame stage advance with the increase of hydrogen fraction in natural gas–hydrogen blends. In addition, the amplitude of ionization currents in both front flame and post flame (including the two peaks) fueled with natural gas gives lower values compared with those fueled with gasoline and hydrogen addition can increase the amplitude. Maximum post flame current shows similar trend to maximum cylinder pressure and it has good correlation between the timing of maximum post flame current and the timing of maximum cylinder pressure. High correlation coefficient between maximum post flame current and maximum pressure is presented.

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1. Introduction

It is well known that a lot of charged particles are generated in the flames. The charged particles including ions and electrons will migrate in vivo direction under an electric field, and ionization current is generated. In the past decades, ionization current generated in spark-ignition engines was used as a new electronic control technique called ionization current method to meet the requirement of emission control and fuel economy. It can also be employed to clarify the mechanism of fuel combustion characteristics. Additionally, due to its low cost, simple structure, no modification to engine and excellent responsibility, the ionization current diagnostics is proved an effective approach in engine and many studies have been...
done on it. The characteristics of ionization current in SI engine fueled with gasoline were widely calibrated, and this technology is currently used on online diagnosis, such as misfire and knock detection, cam phase determination, air–fuel ratio estimation, cylinder pressure estimation and peak cylinder pressure position estimation [1–8]. Currently, most SI engines are operated with inductive ignition system as it has large ignition energy and reliability. However, large ignition discharge will disturb the ionization current during the combustion. Eriksson et al. [9] and Yoshiyama [10] reported that the ion current during the initial flame propagation was masked by the current of spark discharge and was hardly detected if long duration of discharge exists after ignition. Wu et al. found that the ionization current was disturbed by ignition discharge when using spark plug as a sensor [11]. How to separate the interference of ignition discharge from ionization current becomes a key issue in the ionization current measurement technology.

As one of clean fuels, natural gas attracts more interest and research due to its higher octane number, higher fuel conversion efficiency, lower HC, CO and NOx emission compared to gasoline engine [12–14]. However, natural gas still remains its disadvantages like relatively large cycle-by-cycle variations and long combustion duration at lean combustion and decreased volumetric efficiency as natural gas occupies part of intake charge compared with gasoline engine [15,16]. To avoid such disadvantage, a blend of natural gas and hydrogen was tested and combustion/emission characteristics fueled with natural gas–hydrogen blends were investigated [17–21]. Hu et al. showed that laminar burning velocity increased and adiabatic flame temperature increased with the increase of hydrogen fraction in their fundamental study on premixed flame [22]. Wang et al. showed that peak cylinder pressure and maximum rate of pressure rise increased and cycle-by-cycle variation decreased when hydrogen was blended with natural gas [23]. Wong and Karim also showed that addition of hydrogen could reduce the cyclic variations [24]. Theoretical study by Karim et al. showed that addition of hydrogen decreased the ignition delay and combustion duration, and could stabilize the combustion process [25]. Study by Thurnheer et al. found that the addition of hydrogen to methane shortened the combustion duration, especially the interval between spark discharge and 5% of mixture burned [26]. Engine fueled with natural gas–hydrogen blends showed low cycle-by-cycle variations and emission characteristics [27,28].

In this study, the ionization current generated in a SI engine fueled with gasoline, natural gas and mixture of natural gas–hydrogen blend are studied. Filtration method called Blind Source Separation (BSS) method on current, in which the independent original signal can be extracted from the statistically independent source signals, is chosen to pick up the ignition discharge from ionization current [29–31]. Since ignition discharge interrupts the detected current, thus, the current is de-noised with BSS method. Furthermore, the temperature at the gap of spark plug is calculated and used to interpret the behavior of ionization current. The study provides further understanding to ionization current signal and comparison on ionization current of engine fueled with natural gas–hydrogen blends and gasoline.

### 2. Experimental setup and procedures

The specifications of multi-fuel engine modified from an HH368Q gasoline engine are listed in Table 1. Fig. 1 shows the schematic diagram of the engine system. Fuel supplying system of the engine consists of a fuel tank, a pressure regulator, and a gas mixer. In the case of gas fuel, the air–fuel ratio is adjusted by a step motor and monitored by an air–fuel sensor. Natural gas and hydrogen in this study have the purities of 96.16% and 99.995%, respectively. Cylinder pressure is recorded by a piezoelectric absolute pressure transducer (Kistler 4075A) with resolution of 0.01 kPa. Inductive ignition system is used and ionization current is detected from spark plug of ignition system. Fig. 2 shows the ionization current measurement circuit. The ionization current measurement circuit connects to the central electrodes of spark plug by an electrical wire. A high-voltage silicon stack, bias and a grounded resister (R, ) is connected. High-voltage silicon stack is used to avoid damage of high voltage of ignition discharge to the measuring circuit. The bias voltage (400 V) is provided by a DC power including an accumulator (12 V) and a DC power block. Under the function of the bias, charged particles generated during the combustion move directionally and form ion current. The ionization current signal is detected from R2 (100 KΩ), and a capacitance in parallel connection to R2 is installed to filtrate the high frequency noise.

### 3. Numerical and de-noising method

#### 3.1. Numerical methodology

The temperature field in combustion chamber and the temperature at the gap of spark plug gap are calculated using the AVL-FIRE simulation code. Combustion chamber in cylinder chooses as the control volume. Differential control equations (based on N–S equation) of mass, momentum and energy conservations are [32,33],

\[
\frac{\rho}{\partial t} = \frac{\partial}{\partial x_i} \left( \frac{D \partial C}{\partial x_i} \right) \tag{1}
\]

\[
\frac{\rho}{\partial t} \frac{\partial U_i}{\partial x_j} = \frac{\partial}{\partial x_i} \left( \frac{D \partial U_i}{\partial x_j} \right) \tag{2}
\]

<table>
<thead>
<tr>
<th>Table 1 – Engine specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>Bore/mm</td>
</tr>
<tr>
<td>Stroke/mm</td>
</tr>
<tr>
<td>Displacement/cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Ignition sequence</td>
</tr>
<tr>
<td>Rated power/kW</td>
</tr>
<tr>
<td>Rated speed/(r/min)</td>
</tr>
</tbody>
</table>
\[
\frac{\partial H}{\partial t} = \rho \frac{\partial q_g}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \bar{U}_j \right) + \frac{\partial}{\partial x_j} \left( \rho \bar{v}_T \right)
\]

(3)

Where \( t \) and \( x \) are time, coordinate of the Cartesian coordinate; subscript \( i, j \) and \( k \) are coordinate direction; \( C, U \) and \( H \) are mass concentration of a species, velocity and enthalpy, respectively. \( \rho, D, \bar{r}, \bar{v}, \mu, \beta_j, \gamma_g \) and \( \tau \) are density, mass flux, molecular diffusion coefficient for a particular species, temperature, pressure, heat conductance, dynamic viscosity coefficient, unit tensor, velocity vector, heat flux and turbulent stress tensor, respectively. The \( k-e \) Model is used in turbulence calculation and Eddy Break-up Model is used in combustion calculation. Simulation is based on the Finite Volume method.

Movable mesh is established with FAME Engine Plus tools. Total number of mesh at top-dead center (TDC) and bottom-dead-center (BDC) are 26893 and 110182, respectively. Initial condition is given in Table 2. The boundary condition of the cylinder chamber is acquired according to experience and given Table 3.

To ensure the calculations process in reasonable time, the calculation for each matrix point starts from 120 °CA BTDC, which is the timing of inlet valve closure and finishes at 80 °CA ATDC, which corresponds to the timing of combustion finished.

Fig. 3 shows the comparison between the calculated and the measured cylinder pressure and maximum cylinder pressure. The results show good agreement between the calculated ones and the measured ones. The difference between the calculated and the measured maximum cylinder pressure is less than 5 percent.

### 3.2. BSS de-noising method

Since ionization current is easily interfered by the spark tail signal generated by discharge of ignition, BSS method is chosen to separate the real ionization current and the spark tail. BSS method means that source signals and mixing mode are unknown, the source signals could be separated from each other.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial pressure</td>
<td>0.98 MPa</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>315 K</td>
</tr>
<tr>
<td>Initial turbulent kinetic energy</td>
<td>16.9 m² s⁻²</td>
</tr>
<tr>
<td>Initial turbulent long scale</td>
<td>0.005 m</td>
</tr>
</tbody>
</table>
other according to detected signal, and the wave of source signals could be achieved. As requested from the BBS method, a couple of detected current signals are required to get the source signals [34], in this paper, two consecutive ionization current signals detected by the spark plug sensor are chosen.

Assuming spark tail \( s_1 \) and ionization current \( s_2 \) could be expressed in vector form,

\[
S(t) = (s_1(t), s_2(t))^T
\]  

\( 4 \)

The consecutive ionization current signals are,

\[
X(t) = (x_1(t), x_2(t))^T
\]  

\( 5 \)

\( x_1(t) \) and \( x_2(t) \) are two mixed signals measured at timing \( t \) where \( t \) is the time or sample index. The detected signal is linear to the source signal,

\[
X(t) = AS(t)
\]  

\( 6 \)

\( A \) is an unknown hybrid matrix. [20,33]

To confirm the separation matrix, \( W \), the transformed output, \( Y(t) \), is the copy or estimating of source signals, \( S(t) \).

\[
Y(t) = WX(t)
\]  

\( 7 \)

In this paper, the Independent Component Analysis (ICA) method is adopted [30]. The ionization current signal is separated by the fixed point calculation method proposed by Hyvarinen in Helsinki University, the FastICA tools for Matlab software developed by Hyvarinen is chosen for the separation [30].

The source signals, \( S(t) \) can be obtained by solving the following function:

\[
[Y, A, W] = \text{FastICA}(X)
\]  

\( 8 \)

4. Results and discussion

4.1. Typical ionization current signal

Fig. 4 plots the typical original ionization signal and cylinder pressure at wide opening throttle (WOT), ignition timing of 23 CA BTDC, and engine speed of 2000 r/min. Figs. 5 and 6 show the calculated temperature at spark plug gap and temperature field in combustion process under the same

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Boundary Type</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>The wall of cylinder head</td>
<td>Solid wall</td>
<td>520 K</td>
</tr>
<tr>
<td>The wall of cylinder sleeve</td>
<td>Solid wall</td>
<td>427 K</td>
</tr>
<tr>
<td>The wall of Piston</td>
<td>Mobile wall</td>
<td>515 K</td>
</tr>
</tbody>
</table>
initial condition. The results show that the ionization current reflects three obvious stages, they are, the ignition stage, the front flame stage and the post flame stage. The ignition stage (from ignition point to the first transition, point 1) is related to the spark tail generated by the ignition discharge.

The front flame stage (point 1 to the second transition, point 2) is related to chemical-ionization process at flame front during early stage of combustion. The reason can be explained as following. By \( \text{CH} + \text{O} \rightarrow \text{CHO}^+ + e^- \), and subsequent charge transferring, \( \text{CHO}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{CO} \), results in a late appearance of the dominant ion \( \text{H}_3\text{O}^+ \) [35]. It is known that peak of front flame is related to large amount of chemiions generated during flame kernel formation [11]. Fig. 6 shows that the flame kernel is formed at 3 °CA ATDC. This is consistent to appearance of peak of front flame at 2.5 °CA ATDC as shown in Fig. 4.

The post flame stage (after point 2) in the ionization current is mainly related to the thermal-ionization process due to high temperature in cylinder. Figs. 5 and 6 show that at 10 °CA ATDC, the flame propagates the whole chamber and large amount of
mixture is burned, and the temperature at the spark plug gap is about 2000 K. The major contributor to ionization current is NO$^+$, because NO molecule with low ionization energy (9.26405 eV) can be easily ionized to NO$^+$ at high pressure and temperature [3,36-39]. The ionization current increases continuously with increasing temperature. Temperature and pressure reach their maximum values at 20°C ATDC, here, the peak ionization current of post flame is presented.

4.2. Average ionization current signal

Ionization current is influenced by combustion, gas flow and air–fuel ratio [40,41], and current varies cyclically or even under same operating condition. Average ionization current of multi-cycles is usually used to relate ionization current and combustion. In this paper, the ionization current of 80 cycles is used for the analysis. Fig. 7 gives the ionization currents and corresponding pressures of 80 cycles. Here the operating condition is the same as that in Fig. 4. It is found that variation of ionization current is larger than that of pressure.

Fig. 8 shows that for most ionization currents, they appear only two peaks, and ignition stage and front flame stage are mixed due to interference of the spark tail generated by discharge. However, for some currents at engine speed of 2000 r/min, the front flame can be discriminated from the spark tail. For all currents at engine speed of 3000 r/min, the front flame is interfered by the spark tail. The possible explanation is that the duration of the spark tail is constant when the duration of ignition discharge generated by the ignition system is fixed. It is well known that high engine speed corresponds to short appearance of flame kernel, leading to the early appearance of front flame stage. Thus, the current at front flame stage is likely interfered by spark tail at high engine speed. As more information on combustion is included in the current at front flame, some combustion information may be lost if front flame is mixed by spark discharge. As post flame stage is not seriously interfered by the spark tail, thus, the post flame stage can be discriminated to most currents.

4.3. Application of BSS method on ionization current

To show the general applicability of BSS method, two signals from spark plug sensor with small difference (as shown in Fig. 9a) and another two signals with large difference (as shown in Fig. 9b) are selected. As shown in Fig. 9a, the ionization current in front flame stage of the former cycle mixes with the spark tail, and the post flame stage is not obvious.
While in the latter cycle, the front flame stage does not mix with the spark tail, and the post flame stage can be discriminated. As shown in Fig. 9b, in the former cycle, the front flame stage is completely mixed with the spark tail, and the post flame can be discriminated. While in the latter cycle, the front flame stage is not obvious and the post flame stage can also be discriminated. These indicate that spark tail affected the current in varying degree.

4.3.1. The de-noised ionization current

Fig. 10a and b show the ionization current and spark tail signal processed by BSS method to the data in Fig. 9a and b, respectively. The average pressure of the two cycles is also provided. As shown in Fig. 10a and b, the ionization current includes two peaks. The timing of the two peaks in each ionization currents appear at $3/_{14}$ CA ATDC and $20/_{14}$ CA ATDC, respectively. This is in good agreement with the timing of the peaks in front flame and post flame as shown in Fig. 9. It is well known that the ionization current (except the ignition stage) includes two stages, the front flame and post flame stages. The first peak (peak of the front flame) in the current is related to the timing of flame kernel development and the second peak (peak of the post flame) is related to the charged particles generated during flame kernel formation and it appears at the timing when flame is fully developed [11]. The timing of post flame in current corresponds to the timing of maximum cylinder pressure arriving [42]. As shown in Fig. 6, at $3/_{14}$ CA ATDC, the flame kernel is fully developed. As shown in Fig. 11, the timing of first peak is in good agreement with timing of

Fig. 11 – Ionization current and pressure under motoring condition.

Fig. 12 – Ignition charge for different fuels.

Fig. 13 – Ionization current for different fuels.
flame kernel development, and the second peak appears at the timing of maximum cylinder pressure reaching (20 °CA ATDC). Thus, the separated ionization current processed by BSS method is the real ionization current generated during the combustion and the two peaks in the separated ionization current reflect the front flame and post flame stage.

4.3.2. Spark tail confirmation

To confirm the spark tail generated by ignition discharge, the engine is operated at motoring condition under same operating condition as in Fig. 9. The measured ionization current signal and cylinder pressure are illustrated in Fig. 11. As shown in Fig. 11, the signal shows only one peak at 5 °CA ATDC. Since no combustion occurs, this signal must be the spark tail signal generated by ignition discharge. As shown in Fig. 10, the timing of peak spark tail also appears at 5 °CA ATDC. Good agreement on timing of spark tail in Figs. 10 and 11 confirms the feasibility and accuracy of BSS method in extracting the spark tail signal. With respect to different amplitudes in spark tail signal at monitoring condition and combustion condition, the possible explanation is that, the equivalent LC concussion circuit is composed by the secondary winding and the spark plug, the spark plug is regarded as the parallel connecting resister and capacitance after ignition timing [43]. Amplitude of the spark tail is related to the capacitance of the gas between gap of spark plug as the L of the secondary winding is constant. The capacitive impedance is related to the property of the gas between spark plug gap.

4.4. Fuel effect on ionization current

Figs. 12 and 13 give the spark tail and ionization currents processed by BSS method based on data in Fig. 8. Corresponding cylinder pressure and the calculated temperature at spark plug gap are illustrated in Figs. 14 and 15 respectively. As shown in Fig. 12, all spark tails appear simultaneously. This again confirms that the spark tail processed by BSS method is independent on combustion. Amplitudes of spark tail vary with fuels, and this is due to varied capacitive impedance of gas between spark plug gap for different fuels.

As shown in Fig. 13, the timings of front flame and the peak in front flame stage fueled with natural gas are postponed compared with those fueled with gasoline, and the timing is advanced with the increase of hydrogen fraction in natural gas—hydrogen blends. The amplitude of ionization current in...
Fig. 16 — Interdependency between $\theta_{\text{max}}$ and $\theta_{\text{pmax}}$ for different fuels.

a Engine speed of 2000 r/min

b Engine speed of 3000 r/min
front flame (including the peak) fueled with natural gas is lower than that fueled with gasoline, and it increases with the increase of hydrogen fraction. The timing of front flame (including the peak) is dependent on flame kernel development. When flame kernel is fully formed, the peak value of ionization current in the front flame will appear [11]. The period of flame kernel formation fueled with natural gas is longer than that fueled with gasoline, and it shortens with the increase in hydrogen fraction in natural gas—hydrogen blends [26]. The front flame in current generated during combustion of hydrocarbon fuels is related to H3O+, and the amplitude of front flame stage is dominated by the density of CHO and OH which are the source of H3O+. Production rates of CHO and OH in natural gas flame are slower than those in gasoline flame and these production rates increase as hydrogen is added [44,45]. Thus, the densities of CHO and OH in natural gas flame are lower than those in gasoline flame, and they increase as hydrogen is added.

As the interference of spark tail on post flame in current is limited, the amplitude of the post flame stage and the timing of maximum value of post flame in Fig. 13 are in good agreement with those in Fig. 8, and this also confirms the validity of BSS method in data processing. The timing of the peak of the post flame in current fueled with natural gas is postponed compared with that fueled with gasoline, and it advances as hydrogen is added in natural gas. The value of the second peak of the current fueled with natural gas is lower than that fueled with gasoline, and it increases with the increase of hydrogen fraction in natural gas—hydrogen blends. The timing of maximum post flame current corresponds to the timing of maximum cylinder pressure [3]. As shown in Fig. 14, the timing of maximum cylinder pressure fueled with natural gas is postponed compared with that fueled with gasoline, and it advances as hydrogen is added. It is well known that the post flame stage is dominated by NO produced during the thermal-ionization process, and the number of NO formed during this process increases as burned gas temperature is increased. As shown in Fig. 15, maximum temperature fueled with natural gas gives the lower value compared with that fueled with gasoline, and it increases as hydrogen is added.

4.5. Relationship between pressure and ionization current for different fuels

Comparison on Figs. 13 and 14 shows that, the timing of maximum cylinder pressure is consistent with that of current second peak. Relationship between the timing of maximum post flame current (θ_{\text{max}}) and the timing of the maximum cylinder pressure (P_{\text{max}}) is a useful parameter in the utilization of ionization current measurement technology. Some researchers tried to use ionization current sensor instead of pressure sensor. The interdependency between θ_{\text{max}} and P_{\text{max}} from 80 cycles for different fuels are shown in Fig. 16. Coefficient (R^2) between any two variables is calculated by the following formula,

\[ x = \frac{1}{N} \sum_{i=1}^{N} x_i \]  

\[ R(x, y) = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y}) / (SD_x \cdot SD_y) \]  

Where \( x_i \) and \( y_i \) represent the specific values of sample \( x \) and sample \( y \) in arbitrary combustion cycle. \( N \) is total number of cycles. \( \bar{x} \) and \( SD_x \) refer to the average value and the standard deviation. Coefficient (R^2) represents the coefficient between sample \( x \) and sample \( y \). The results show that R^2 is over 0.9 for all fuels, and this reveals good correlation between θ_{\text{max}} and P_{\text{max}} regardless of fuels used. Slightly weak correlation between θ_{\text{max}} and P_{\text{max}} fueled with natural gas is presented compared with that fueled with gasoline, and strong correlation is presented fueled with natural gas—hydrogen blends. Therefore, it is feasible to use θ_{\text{max}} to predict P_{\text{max}} from this correlation for engine diagnostics, and the prediction becomes highly precise as engine operates on natural gas—hydrogen blends.

5. Conclusions

Investigation on ionization current characteristic in a spark-ignition engine fueled with natural gas, natural gas—hydrogen blends and gasoline was conducted. Blind Source Separation (BSS) de-noising method is employed to separate the ionization current signal from the interference of spark tail generated by ignition discharge. Main results are summarized as follows:

1. Primary ionization signal measured in the cylinder cannot extract the ignition stage and the front flame stage, due to the interference of spark tail generated by discharge. The post flame is not interfered seriously. The current in front flame stage is more likely interfered by the spark tail at high speed.
2. BSS method can separate spark tail and real ionization current. Real ionization current contains the front flame and the post flame stage. The timing of peak current at front flame is near TDC and the timing of peak current at post flame stage corresponds to the timing of maximal pressure.
3. Appearances of front flame and post flame (including the two peaks) fueled with natural gas are postponed compared with that fueled with gasoline, and they advance when hydrogen is added in natural gas. Amplitudes of ionization current in both front flame and post flame (including the two peaks) give lower values fueled with natural gas compared with that fueled with gasoline, and they increase as hydrogen is added.
4. Good correlation between the timing of maximum post flame current and the timing of maximum cylinder pressure is presented regardless of fuels used.

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