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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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ABSTRACT

Investigation on ionization current characteristic in a spark-ignition engine fueled with natural gas, natural gas–hydrogen bends 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.

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

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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 NO_x 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_2) 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 R_2 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],

$$\widehat{\rho}\ \frac{D\widehat{C}}{Dt} = \widehat{\rho}\ \widehat{\dot{r}}\ + \frac{\partial}{\partial x_j}\left(D\frac{\partial \widehat{C}}{\partial x_j}\right) \tag{1}$$

$$\widehat{\rho}\ \frac{D\widehat{U}_i}{Dt} = \widehat{\rho}\ g_i - \frac{\partial \widehat{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial \widehat{U}_i}{\partial x_j} + \frac{\partial \widehat{U}_j}{\partial x_i} - \frac{2}{3}\ \frac{\partial \widehat{U}_k}{\partial x_k}\right)\delta_{ij}\right) \tag{2}$$

Table 1 – Engine specifications.

Item	Specifications
Bore/mm	68
Stroke/mm	72
Displacement/cm^3	796
Compression ratio	9.4
Ignition sequence	1-3-2
Rated power/kW	26.5
Rated speed/(r/min)	5500