Fuel 190 (2017) 444–450

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Near-engine-condition simulation of ionization in pre-ignition based on chemical kinetics

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HIGHLIGHTS

- Effectively pre-ignition diagnosis is achieved by in-cylinder ion current signal.
- The near-engine condition boundary of ionization is investigated based on chemical mechanism.
- The shockwave model simulates the pre-ignition condition and explains the "pre-ignition" ion current formation process.

ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 6 September 2016
Accepted 29 September 2016
Available online 9 November 2016

Keywords:
Ion current
Pre-ignition
Chemical kinetics
Gasoline direct injection

ABSTRACT

The pre-ignition is very challenging for modern gasoline engines with high pressure boost and gasoline direct injection (GDI) system. Except optical imaging method, effective pre-ignition diagnostic methods are very limited. This paper presents the recent research in the feasibility of using ion current for pre-ignition diagnosis. In agreement with the theory of the ion current based pre-ignition diagnosis, this paper summarizes the simulation studies of the ionization process using chemical kinetics under the equivalent pre-ignition conditions. The simulations are conducted under both constrained boundary conditions and shockwave compressed conditions. The research results indicate that the equivalence ratio of active ionization is in the range of '0.8'–'1.6'. The pressure has insignificant influence on the reaction rate of ionization in low temperature (<1400 K) region. The critical temperature for active ionization is found as 1300 K as well. The combustion process in the shockwave compressed zone depends on the shock speed. A high shock speed (1100 m/s) causes one-stage combustion and a low shock speed (990 m/s) causes two-stage combustion. The start of combustion in both combustion modes can be detected effectively through the ion current. As the combustion temperature raised by shockwave compression reaches 3200 K, the concentrations of electron in ion current of both combustion modes are high enough for ion current measurement.

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1. Introduction

High pressure boost and gasoline direct injection (GDI) have the potential of enhanced fuel economy of internal combustion (IC) engines. Some researchers showed that the maximum indicated efficiency of the spark ignition (SI) engine equipped with GDI and boost system is approaching 40% [1]. However, the recent progress of GDI SI engine has been challenged by occurrence of pre-ignition, which has risks of super knock, under low speed and high load operating conditions [2,3]. Compared with the conventional knock, the formation mechanism of the super knock caused by pre-ignition is different [4]. The super knock is caused by events before spark ignition, and these events are assigned to "Pre-ignition". The resulting super knock is of much stronger intensity and higher propagation speed which even causes detonation wave inside a cylinder and may result in engine damage easily [5–7]. Therefore, avoiding and preventing occurrence of super knock is important. Recent investigations are focused on both the formation mechanism and diagnosis of pre-ignition and super knock [8].

In current researches, pre-ignition in the engine is mainly and directly detected by optical imaging method before it can be detected by in-cylinder pressure [9]. Although the optical method is effective for pre-ignition detection, it is only for research work and unlikely useful for large scale production of engines. In this case, there is still lack of an effective method for determining

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http://dx.doi.org/10.1016/j.fuel.2016.09.084
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pre-ignition before it is detected by in-cylinder pressure or acoustic knocking sensor signal. Ion current signal has been shown feasible for pre-ignition detection in current combustion cycle [10]. Actually the feasibility of using ion current for the combustion detection in IC engine has been reported over the last 20 years. The researches have shown that ion current signal contains the rich information of combustion intensity, combustion phases and combustion reliability [11–13]. Based on the close correlation to in-cylinder combustion pressure, ion current has been also employed for cycle-by-cycle and even in immediate cycle abnormal combustion (such as misfiring, knocking and even pre-ignition) diagnosis [14–16]. Compared to the knocking diagnosis, the pre-ignition diagnosis based on ion current is identified easier with high accuracy by directly comparing ignition timing and ion current timing. Even though pre-ignition has two different types ('low speed pre-ignition' and 'run-away pre-ignition') which have different causes [17], the ionization process in the flame should be the same according to the ionization theory of hydrocarbon fuels [18]. Thus, the utilization of ion current for pre-ignition determination is reasonable. Furthermore, whether the pre-ignition is caused by hot surface or random hot spot, the unburned zone in the boundary region of combustion chamber would be compressed and ignited after the initial flame kernel appears [19,20]. In this case, the mechanism of this detection method based on ion current will improve with greater understanding.

In this research, based on the previous experimental pre-ignition detection with ion current signal, the ionization in the pre-ignition caused by random hot spot is investigated with numerical modeling. With this investigation, the chemical kinetic mechanism of ion current based pre-ignition determination is understood better.

2. Pre-ignition detection with ion current signal

During the combustion of hydrocarbon fuel, there are minor reactions that generate ion and electron pairs. Although the reactions are minor, it is relatively easy to detect the electrons. The key reactions, which are believed responsible for the production of electron and H_3O^+ from hydrocarbon fuel, are shown as reactions (R1)–(R5) [18]. Although CHO^+ is the primary ion product, it is consumed by reaction (R2) rapidly. The dominant positive ion is H_3O^+, which can also undergo a highly exothermic dissociative-recombination with an electron as reactions (R3) and (R4) proceed. As the rates of both reaction (R3) and (R4) are slow, electrons and H_3O^+ are found in high concentration in the flame reaction zone. Because of their low mass, electrons move much faster in the electric field and thus become the main carrier of ion current.

$$CH + O \rightarrow CHO^+ + e^- \tag{R1}$$

$$CHO^+ + H_2O \rightarrow H_3O^+ + CO \tag{R2}$$

$$H_3O^+ + e^- \rightarrow H_2O + H \tag{R3}$$

$$H_3O^+ + e^- \rightarrow OH + H + H \tag{R4}$$

$$CHO^+ + e^- \rightarrow CO + H \tag{R5}$$

The ion current detection system is illustrated in Fig. 1. Spark plug is used as an ion current sensor in this system. A DC bias-voltage is applied on the spark plug forcing the ion current. As the original ion current is normally at the level of μA, the resistor 1 converts the ion current into a voltage which can be easily measured. High voltage diode D1 and D2 isolate the spark coil from the ion current loop. Thus the ion current signal is measured without interference from the spark ignition event with this dual diode arrangement.

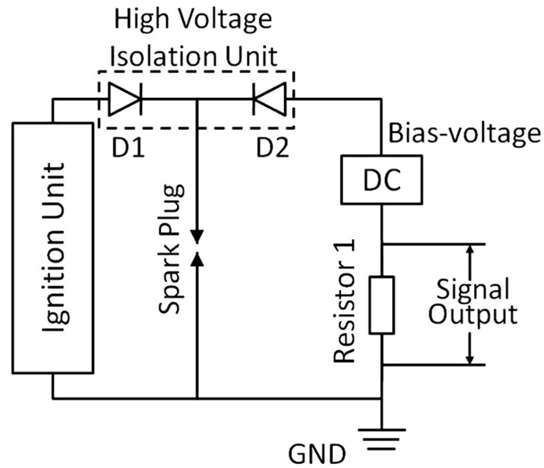

Fig. 1. Schematic of dual diode ion current detection system.

Fig. 2 presents the measured ion current signal of the pre-ignition caused by random hot spot with different intensities in previous study. The data was measured in a boosted GDI engine [16]. Based on the in-cylinder pressure, the burned mass fraction has been reflected by the calculated total released energy during the combustion. When comparing the burned mass fraction to the spark timing, both cycles in Fig. 2 are significantly pre-ignited. Even though the starts of combustion (SOC) in the two pre-ignition cycles are different, the amplitudes of the ion current signals exceed 5 V rapidly just after random SOC, which means ion current reaches 5 μA in this case. Furthermore, the ion current signal amplitude only reaches 1.9 V when 15% of fuel has already burned in case 1, but in case 2, the ion current signal amplitude even exceeds 3 V when 8% of fuel has burned. Thus the ion current signal is much stronger at the same burned mass fraction when SOC is earlier. Under this situation, with ion current, pre-ignition can be detected effectively and even has possibility of being inhibited with the fuel re-injection in-combustion-cycle [16]. This is also helpful for both pre-ignition research and preventing pre-ignition in production vehicles. However, in normal combustion under the same operation condition, the ion current signal lags behind the combustion, and the amplitude of ion current signal is only 1.6 V in average when the combustion pressure already reaches 5 MPa. In this case, compared with normal combustion,

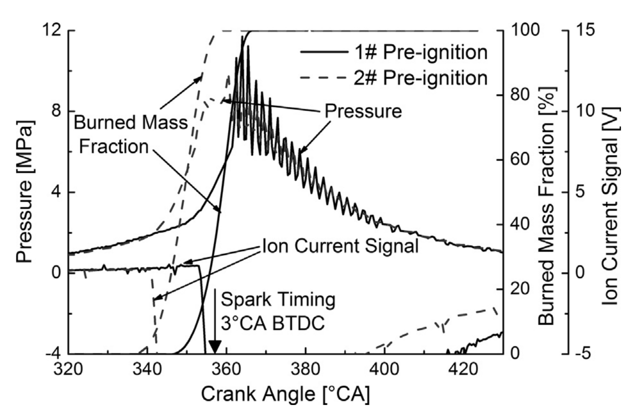

Fig. 2. In-cylinder pressure, burned mass fraction and ion current signal of pre-ignition cycles (engine speed = 2000 r/min, IMEP = 1 MPa, Boost pressure = 0.12 MPa).

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