Method of Ion Current Detection for HCCI Combustion on SI/HCCI Dual Mode Engine

Guangyu Dong, Zhijun Wu. Liguang Li and Fafa Liu.Yingnan Guo

Abstract—**With the advantages of high thermal efficiency and extra low NOx and soot emissions, homogeneous charge compression ignition (HCCI) combustion has become a promising combustion method. Comparing with the SI engine or diesel engine, it is hardly to control combustion phase and combustion period on a HCCI engine directly. Hence, sensing of combustion phase and combustion state is very important for HCCI engine control. In this paper a method of detecting ion current signal as the feedback of combustion characters was discussed through a series of experiments on a gasoline HCCI engine. When the engine operated in pure HCCI mode, the ion current was measured and several parameters were abstracted from ion current waveform in order to investigate the relationship between the ion current and the combustion characters. Simultaneously, the in-cylinder pressure was measured and the rate of heat release was calculated. Experiment results show that there is a strong correction between HCCI combustion phasing and ion current signal. On the other hand, the relationship between ion current and combustion phasing was also discussed when the engine operated under spark assisted HCCI mode. Thus through a set of parameter definition the influence of ignition coil discharge to ion current also be researched.**

I. Introduction

HOMOGENEOUS charge compression ignition which firstly researched by Onishi et al and Noguchi [1] et al in 1979.Now, it is expected to become a next-generation combustion technology that can achieve both low NOx emission and improvements in fuel economy. But one problem of HCCI combustion is to directly control combustion timing and the rate of heat release [2]. In order to improve combustion process and enhance combustion efficiency, it must control combustion timing and make it occur around top dead center [3]. Generally speaking, there are several indirect ways to control the ignition of HCCI combustion such as exhaust gas recirculation (EGR), air preheating, supercharging or variable compression ratio (VCR) [4]. Hence, a feed back of combustion state becomes very important to ensure the rate of heat release should be controllable to avoid knocking or misfire occurs during combustion process.

The spark plug, which ignites the combustible mixture in internal combustion engines, has been investigated as an electrical probe for in-cylinder diagnostics for a long time [5]. Many experiments using burners and constant-volume combustion chambers were conducted in early research. The sensor measures the electric current through the gas in the vicinity of the electrode gap. The combustion process affects the electrical properties of the gas. Thus, the sensor signal contains information about the conditions in the combustion chamber. One important advantage is that this information can be retrieved without inserting any additional equipment into the combustion chamber. Since 1990s, there has been a greater interest in the ionization sensing technique for spark ignition (SI) engine [6]. But the relationship between the ion current and combustion is not clear because of the complexity of ion formation mechanism, In particular, this method is mostly used to diagnose abnormal combustion, such as knocking and misfire, but it is not clear whether combustion diagnosis such as this can be applied to all engines over a wide range of operating conditions.

Differs from flame propagation because of the use of spark ignition, HCCI combustion is believed that occurs almost simultaneously with multipoint auto ignition [7]. This character of HCCI combustion provides a possibility to get the combustion information more reliable by ion current feedback [8]. Fortunately, gasoline-fuelled HCCI engines usually need spark plugs in order to operate in SI combustion mode. Therefore, even if the spark plug is used as an ion current probe, the method has the possibility of monitoring the overall reaction in HCCI combustion.

This paper discussed a method of combustion parameter feedback utilizing flame ionization measurement for HCCI combustion mode on a SI/HCCI dual mode engine. These basic investigations were carried out in HCCI engines with charge-air heating and a set of electrical hydraulic valve (EHV) system under limited engine conditions, such as constant engine speed and load. When the engine operated in pure HCCI mode, the ion current was measured and several parameters were abstracted from ion current waveform in order to investigate the relationship between the ion current and the combustion characters. On the other hand, spark assisted HCCI also been applied on the test engine. Recent researches have shown that SI has an effect on HCCI combustion under certain operation conditions. Fuerhapter et al. [9] mentioned that SI could be used to stabilize the HCCI combustion at low load on an AVL CSI engine. Milovanovic [10] found that SI might trigger auto-ignition at the transient operation from SI to HCCI mode under internal EGR conditions. Hence, the method of combustion information extraction under spark assisted HCCI mode also discussed in this paper.

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II. BASIC THEORY OF ION SENSING TECIHNOLOGY

Ion current signals have long been investigated as a combustion diagnostic tool. The ionization process during combustion of fuel in the cylinder is basically composed by a complex set of thousands of chemical reactions [11]. Generally speaking, this process can be divided mainly into two phases by the essential mechanism of the ionization process in different periods [12].The first phase of an ion current signal which arose by the combustion is defined as the "flame front phase". This phase is related to the combustion process in the flame kernel. It depends on the front flame propagation and the ion probe position within the combustion chamber. The source of the current during this phase is mainly related to chemical-ionization processes. The second phase is defined as the "post flame phase". The ionization during this phase is due to the high temperature inside the combustion chamber. And the most dominative ion production mechanism in this phase is the slow forming Nitric Oxide by means of the extended Zeldovich mechanism [13].

Compared with SI combustion, HCCI combustion is believed that occurs almost simultaneously with multipoint auto ignition and its reaction temperature is much lower. Hence, the important positive ions appeared in HCCI combustion are generated by the chemical ionization reaction, and the principal mechanism has been explained as follows:

$$CH+O \rightarrow CHO^{+}+e^{-} \quad (1)$$

$$CHO^{+}+H_2O \rightarrow H_3O++CO \quad (2)$$

$$H_3O^{+}+e^{-} \rightarrow H_2O+H \quad (3)$$

III. EXPERIMENT METHOD

The investigation was performed in a modified single cylinder production diesel engine. The schematic diagram of the test bench is shown in Figure 1.

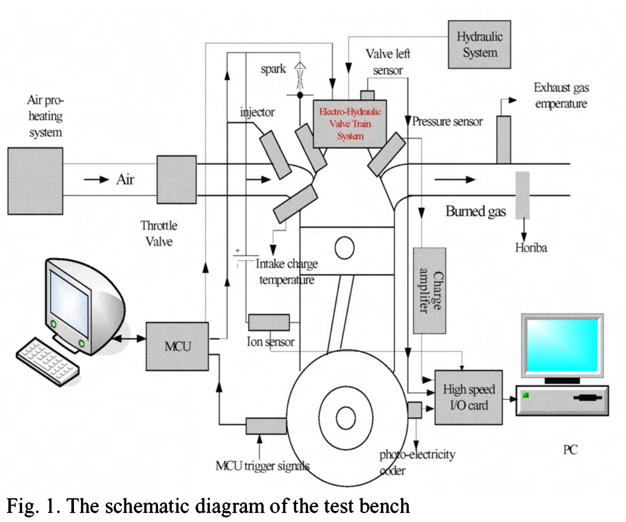

Fig. 1. The schematic diagram of the test bench

The compression ratio decreased from 17 to 11.5 to meet the requirement of operating HCCI and SI combustion mode in this engine. The fuel was injected into the intake pipe to form homogeneous charge. Currently there are many approaches to obtain HCCI combustion, and the commonly used include the intake charge preheating, exhaust gas recirculation, variable compression ratio, dual fuel injection, and so on. Here the HCCI combustion was achieved by a air preheating system and a set of EHV system. When the engine operated in HCCI mode, the intake air should be preheated, while in SI, the inhaled mixture temperature should be the same as room temperature. Table 1 is the specifications of the engine.

TABLE I
SPECIFICATIONS OF THE ENGINE

Engine Type	Single Cylinder,Water coolant
Bore and Stroke	105×11 5mm
Compression Ratio	11.5
Cylinder Number	1
Fuel Injection Type	PFI
Fuel Type	93# Gasoline
Combustion Chamber Type	Swirl

Figure 2 is the ion current measurement system which applied the spark plug as the ion sensor. A 450V bias DC voltage is supplied by a DC/DC converter connected to the battery to achieve ion current when combustion occurred. A resistor is connected in series between the positive electrode and spark plug. Two zener diodes are used to insulate the ion current measurement system form the ignition system. When the bias DC voltage connected to positive electrode of spark plug , the negative electrode of spark plug, cylinder head and the cylinder wall could touch the positive ions for achieving bigger ion current amplitude when combustion occurred.

During the experiment, the engine operated in SI cold starting up and warming-up modes. A thermal management system operated to control the intake temperature and a set of EHV used to change the valve timing from SI mode to HCCI mode. Then the ion current can be observed under both pure HCCI mode and spark assisted HCCI mode.

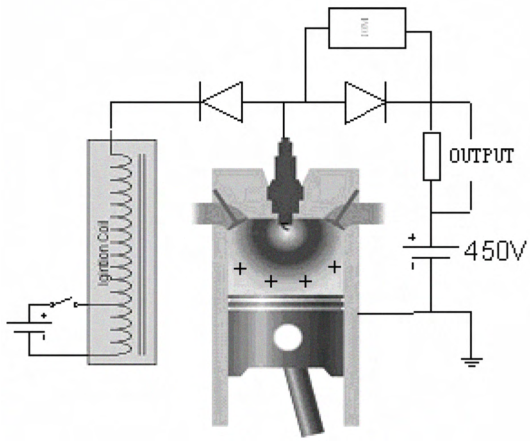

Fig. 2. Ion current measurement system

IV. Results and Discussion

A. Ion current under HCCI mode

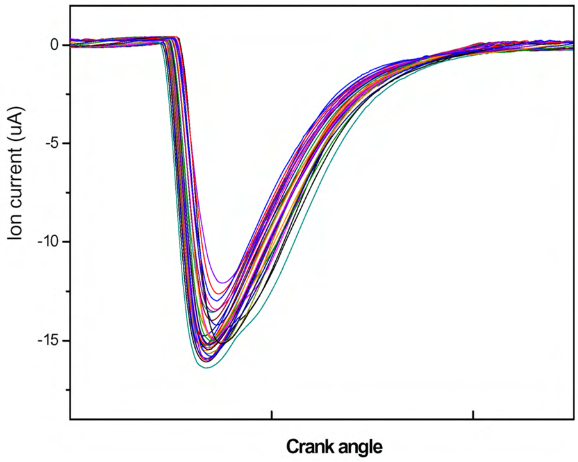

Fig. 3. Ion current waveform under HCCI mode

Figure 3 shows the ion signal collected when the engine operated in HCCI mode with a 1000 rpm engine speed and the intake charge temperature keeps 373K. Generally speaking, the discharging of ignition coil and the flame propagation process will greatly influence the stability of ion signal. But these two factors do not exist in HCCI mode. Hence, it can be seen that the ion current signal achieved in HCCI mode is far more stable comparing with SI engines.

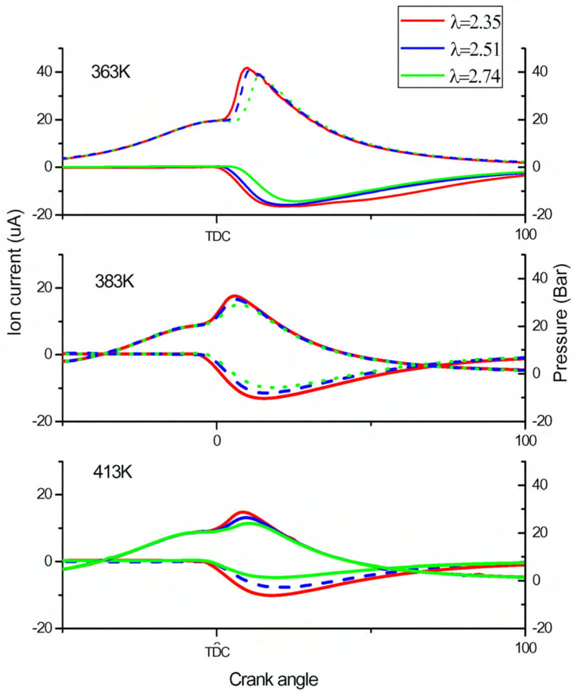

Fig. 4. Ion current variation versus to cylinder pressure

Figure 4 shows the typical mean signal of pressure, and ion current with different charge temperature for gasoline. The engine speed keeps 1000 rpm in this case. From the figure it can be seen that the ion signal varied obviously when the temperature and lambda varied, and the waveform of both cylinder pressure and ion signal changed with the same tendency. When the charge temperature increases, the amplitude of cylinder pressure and ion signal are both decreases and the peak of them are advanced.

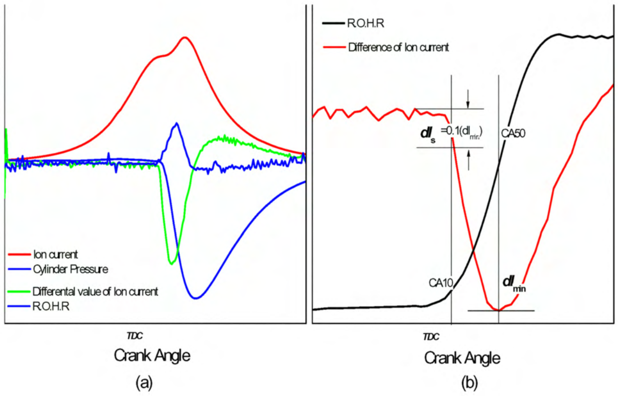

Fig. 5. Parameter definition of ion current

For achieving the information about the combustion phase directly form the ion signal, the relationship between the ion current and rate of heat release (R.O.H.R) should be abstracted by some way. Figure 5 (a) is the relationship between cylinder pressure, heat release ratio, ion signal and differential value of ion signal. It is shown that the differential value of ion signal is well corresponding to heat release ratio. Figure 5 (b) shows the parameter definition method for using ion signal to estimate the combustion phase. Here the crank angle versus to minimal value of ion current difference is defined as dImin. And the crank angle where the differential value of ion signal equals to 10% of dImin is defined as the dIs. The relationship between dIs and the crank angle versus to 10% heat release (CA10),along with the relationship between dImin and CA50 will be discussed as follows.

Figure 6 shows the relationship between dIs and CA10, along with the relationship between dImin and CA50 when the intake charge temperature is 373K. From this figure it can be seen there is a good correlation between dIs and CA10, and dImin and CA50. Figure 7 also shows the same relationship with higher temperature of 413K. And the figure also shows that dIs and dImin are well correlative with CA10 and CA50.

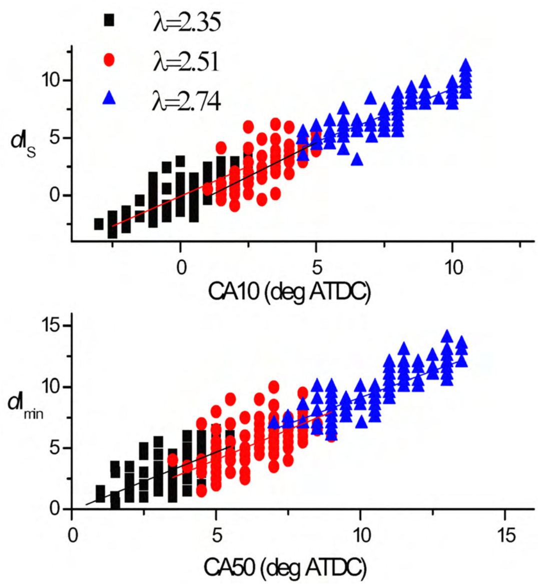

Fig. 6. Relationship between ion current and R.O.H.R with intake charge temperature of 373K

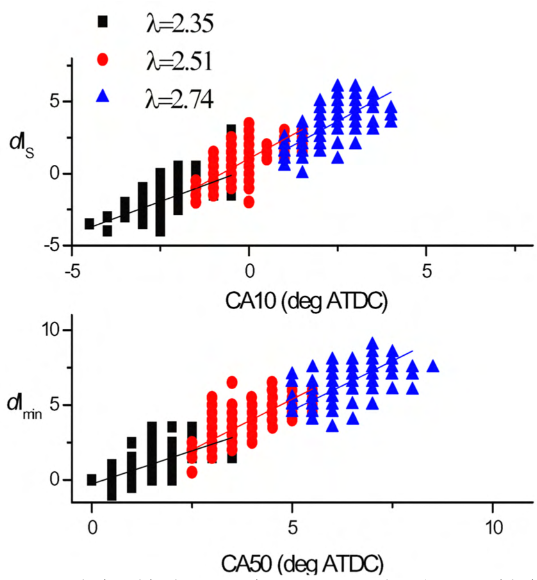

Fig. 7. Relationship between ion current and R.O.H.R with intake charge temperature of 413K

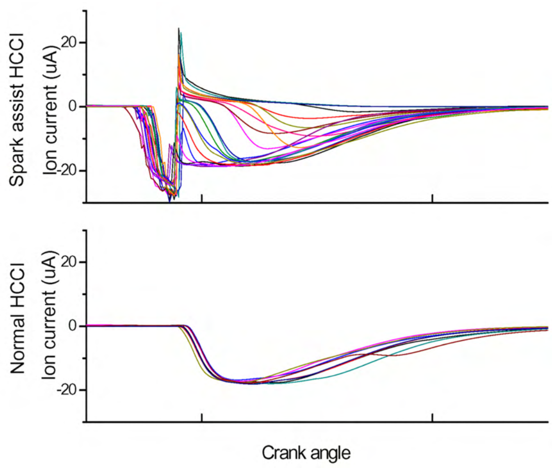

Fig. 8. Ion current with ignition coil discharging

B. *Ion Current under Spark Assisted HCCI Mode*

When the temperature and concentration of mixture at TDC is just slightly lower than the auto-ignition conditions, at this status, misfiring and knocking occur intermittently. Spark ignition provides additional energy input with fast response and is a reliable method to trigger HCCI combustion. In this paper the ion current under spark assisted HCCI mode is researched to discuss the possibility of applying ion current as a feedback of combustion phase. Generally speaking, it is a complex job to observe the ion current on SI engines due to 3 factors: discharge of ignition coil, flame propagation and the instability of combustion process. Fortunately, spark assisted HCCI combustion is a kind of combustion with limited influence of flame propagation and high degree of stability. Thus, the influence of ignition coil discharging is isolated and can be discussed individually.

For achieving a fully understand of influence of ignition coil discharging to the ion current, the spark ignition was firstly provided under the condition of 1000rpm engine speed and 413K intake charge temperature. Though spark assist is not needed when the engine operated under such a condition, but the influence of flame propagation and instability of combustion can be ignored in such a case.

Figure 8 shows the influence of ignition coil discharging to ion current. In this figure it can be seen that ignition coil discharging will greatly influence the ion current waveform (as shown in upper figure) even the combustion process is highly stable (as shown in nether figure). Generally, a ringing phenomena will occurred when spark provided. Hence the state of ignition circuit is uncertain because the ringing phenomena. Then the uncertain state of the circuit will lead to uncertain ion current even the combustion events are same.

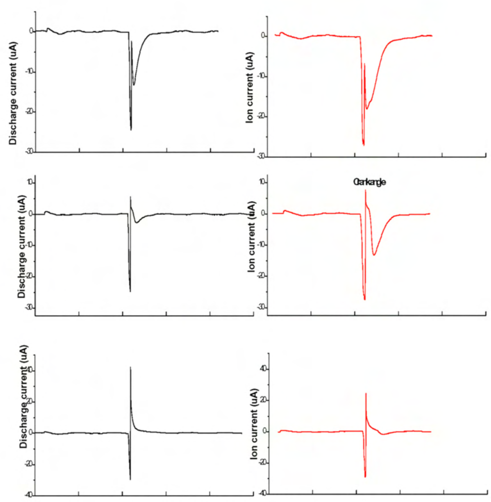

Fig. 9. Ignition coil discharging versus to ion current

Figure 9 shows several typical ion current under different coil discharging state. Hence another phenomena also can be seen that more acutely the ignition coil discharge, more lately the ion current waveform retard in this figure.

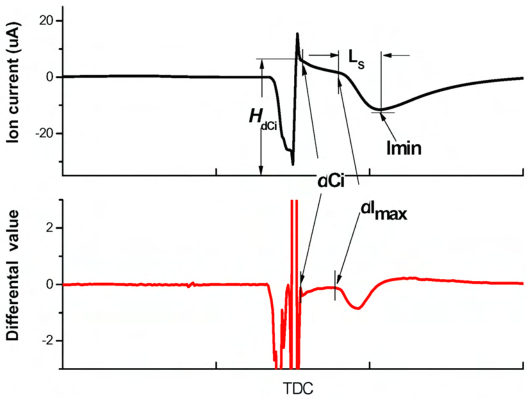

Fig. 10. Parameter definition of ion current under spark assisted HCCI condition

For clearly describing the influence of ignition coil discharging to ion current, a set of parameter was defined as shown in Figure 10.Here, the 1st inflexion of ion current differential value after coil discharging was defined as dCI, the minimal point of ion current was defined as Imin, the max of ion current differental value between coil discharging and Imin was defined as dImax, the duration between dCI and Imin was defined as LS, and the height of dCI point was defined as HdCI.

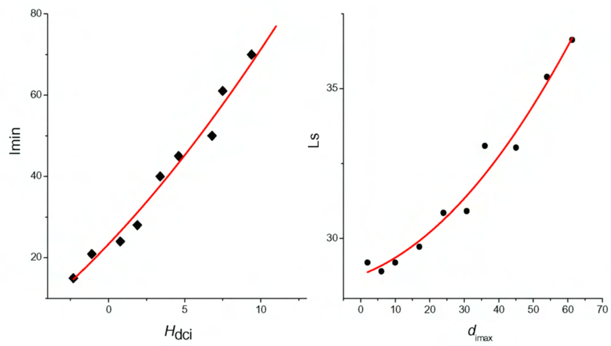

Fig.11 relationship between Imin and HdCI, Ls and dImax

Figure11 shows that when HdCI increased, the position of Imin will retard fellows a quadratic equation. And when the value of dImax increased, the value of Ls is also increased. So, for extract the combustion phasing from ion signal with spark assist status, a equation can be got by the fit of these two curve.

Figure 12 is the ion current under the condition of spark assisted HCCI at HCCI critical status of lambda equals to 3.12 and intake charge temperature keeps 363K. Form this figure it is also can be seen that the influence of ignition coil discharge to ion current also in a same way in such a engine operation condition.

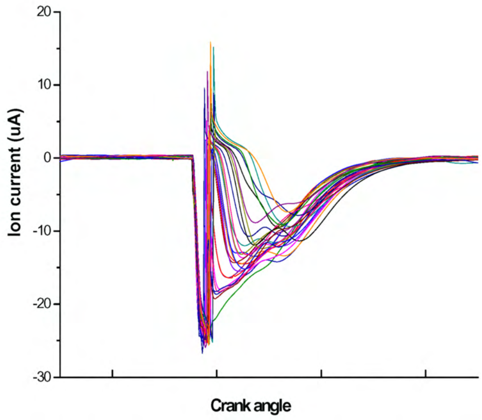

Figure.12. Consecutive ion current signals under spark assisted HCCI mode

V. Conclusion

In this paper a method of detecting ion current signal as the feedback of combustion characters was discussed through a series of experiments on a gasoline HCCI engine. Ion current and cylinder pressure was measured for various charge temperature, air-fuel ratio in HCCI mode. Experiment results show that there is a strong correction between HCCI combustion phasing and ion current.

In the case of lambda equals to 2.35, 2.51 and 2.74, there is a good correlation between the location of minimal value of ion current difference (dImin) and location of 10% heat release ratio(CA50) when the intake charge temperature equals to 373k.

The location of differential value of ion signal equals to 10% of dImin(dIs) also well correlative with the location of 50% heat release ratio with the lambda of 2.35,2.51 and 2.74 when the intake charge temperature equals to 373k.

In the case of intake charge temperature increase to 413K, the good correlation between CA50 and dImin, CA10 and dIs also existed.

Under spark assisted HCCI mode, the ignition coil discharge will great influence ion current waveform. When HdCI increased, the position of Imin will retard fellows a quadratic equation. And when the value of dImax increased, the value of Ls is also increased.

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