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Investigation on characteristics of ion current in a methanol direct-injection spark-ignition engine

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HIGHLIGHTS

- Combustion of methanol was detected with ion current method.
- Typical ion current has two peaks.
- Ion current can reflect the knock intensity.

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ABSTRACT

Investigation on the characteristics of ion current in a direct-injection stratified-charge engine fueled with methanol was conducted. The test engine is a retrofitted 4-cylinder diesel engine with installation of a spark plug. Ion current was measured using the spark plug as ion sensor. Cylinder pressure was recorded and cylinder average temperature was calculated. The band-pass filtering and low-pass filtering method were chosen to extract the frequency and amplitude of ion current for the knock evaluation. Results shows that ion-current signals measured in the methanol engine under normal combustion conditions contain the front-flame stage and the post-flame stage. The characteristic parameters of ion current relate to the methanol engine operating conditions. The pattern of ion current shows high frequency oscillation under the knock conditions, and the amplitude of ion current frequency can reflect the knock intensity. The frequency of ion current signals under knock conditions is ~7 kHz. The knock evaluation index determined by band-pass filtering and low-pass filtering methods is in good agreement with the experimental results. Ion current method can effectively diagnose the knock of direct-injection methanol engines.

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1. Introduction

With increasing concern on global energy and strengthening of exhaust emission, much effort has been made on engine electronically controlling techniques and the utilization of alternative fuel. The detection of combustion in cylinder with sensors is a key issue in electronic control field. Compared with expensively optical sensor and pressure recorder, ion current measurement draws more attention of researchers because of its cost-effective, simple structure and excellent respond characteristics. Thus much research work on ion current measurement has been conducted on combustion diagnosis of internal combustion engines, such as the estimation of air–fuel ratio, mass fraction burned and heat release using the ion current method [1,2]. Additionally, the abnormal combustion of spark-ignition engine, such as knock, pre-ignition and misfire had also been investigated using the ion current method [3–8].

Previous studies showed that a lot of charged particles including ions and electrons are generated in the hydrocarbon fuel flames. The charged particles will migrate in vivo direction under an electric field, leading to the generation of ion current [9]. The characteristics of ion current in engine with fossil fuels have been widely calibrated, such as the appearance timing, peak value, integral values, which were used to correlate with the combustion characteristic parameters [8,10–12]. This technology is currently used on engine-online diagnosis, such as misfire, knock detection, cam phase determination, the estimation of air–fuel ratio, cylinder pressure and peak cylinder pressure position. Ogata [13] calculated the integral of the ion current, and the calculation results were defined as the ion intensity. He found a strong relationship between ion intensity and NOx emission under various operating conditions.

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Nomenclature

CR	compressed ratio	φ	Crank angle (°)
CNG	compressed natural gas	MBT	optimal spark advance for the best torque of the engine
DISI	direct-injection spark-ignition	$dp/d\varphi$	changing rate of pressure
BTDC	before top dead center	FFT	Fast Fourier Transform

Henein et al. [14] found that the second and third ion current peaks in an automotive common rail diesel engine were related to the mixing and diffusion controlled combustion fractions and strongly depended on the temperature of combustion products. With the increasing concern on alternative fuels, some researchers investigated the ion current on alternative fuels. Frank et al. [15] installed injection systems in a constant combustion cell for the injection of compressed preheated air and compressed methane, and they found the occurrence of peak when flame touched the cathode. Zheng et al. [16] investigated the correlations of ion current integral, cylinder peak pressure and indicated mean effective pressure under different operating conditions in a spark ignition (SI) engine fueled by compressed natural gas (CNG) with 20% (in volume) nitrogen enrichment. Zhang et al. [4] established correlations of ion current integral, cylinder peak pressure and indicated mean effective pressure under different operating conditions in a spark ignition (SI) engine fueled with compressed natural gas (CNG).

Using light alcohols in spark-ignition engines can improve energy diversity and offer the prospect of carbon neutral conversion. As one of clean alternative fuels, methanol is a renewable energy resource since it can be produced from a great number of materials, such as natural gas, coal and bio-logical materials [17]. Moreover, methanol is well accepted because of its higher octane number, higher fuel conversion efficiency, lower HC, CO and NO_X emission compared to gasoline engine [18]. The high octane rating of methanol makes it an appropriate fuel for high compression ratio (CR) engines with high power. Bahattin et al. improved the performance and reduced emissions by using pure methanol at high CR (raising from 6:1 to 10:1) in a small engine with low efficiency. Their study showed that significant reductions in CO, CO_2 and NOx emissions were realized when methanol was used instead of gasoline in SI engines [17]. The vaporization latent heat of methanol is high. When methanol is directly injected into the intake port in the spark ignition engine, there remains many disadvantages like poor evaporation, auto-ignition and poor low-temperature startup performances compared with gasoline engine [19]. Thus, to avoid such disadvantages, researchers used the spark plug or mixed with inflammable fuel to enhance the ignition performance of the engine fueled with methanol. Ji et al. investigated the effect of hydrogen addition on the performance of a methanol engine under part loads and lean conditions, and they showed that the constant volume combustion efficiency of the 3% hydrogen-blended methanol engine was also higher than that of the pure methanol engine [20]. Vancoillie et al. assessed the potential efficiency benefits and emission reductions by employing methanol in flex-fuel and dedicated engines, and their results demonstrated that methanol could be used in dedicated engines with diesel-like efficiencies and emission levels comparable to or lower than gasoline [21]. Study by Zhen et al. found that with the increase in EGR, thermal efficiency was greatly reduced and knock occurrence timing was postponed [22].

Although ion current diagnosis on engine fueled with fossil and CNG (compressed natural gas) have been studied extensively, little attention has been made to the use of ion current method in methanol engine. This study focuses on the characteristic parameters of ion current generated in a direct-injection spark-ignition (DISI) engine fueled with methanol under normal operating condition and knock condition. Firstly, the characteristic parameters of typical ion current are analyzed, and the effect of operating condition on ion current is investigated. Secondly, two filtering methods including band-pass and low-pass filtering methods are chosen to analyze the ion current under knock conditions, and the frequency and amplitude are extracted from the measured source ion current signals to evaluate the knock degree. Furthermore, the average temperature and heat release are also calculated and used to interpret the behaviors of ion current under different engine-operating conditions. Our results are beneficial to the understanding of ion current signals in methanol engine and propose ion current index for the evaluation of abnormal combustion of the engine fueled with methanol.

2. Experimental setup and procedures

The detailed specifications of the spark-ignition methanol engine modified from an 4102QB diesel engine has been reported in Ref. [23]. The purity of methanol in this study is 99.9%. Cylinder pressure was recorded by a piezoelectric pressure transducer (Kistler 6125A). Fig. 1 shows the developed complex-guided stratified-charge combustion system, and a spark plug was equipped at the side of cylinder head. Methanol was injected into the cylinder chamber from the nozzle and mixed with fresh air, and the spray upstream of the deflector equipped in the piston made the mixture move to the spark plug. As shown in Fig. 2, the ion current measurement system is connected with the central electrodes of the spark plug by a high tension wire. Since a high-energy ignition system including electronic ignition components (6TS2107 type) and a high-energy ignition coil (DQ40) was used to ignite the mixture, a high-voltage silicon stack (180 kv/2 A) was used to avoid the high ignition discharge. Then a DC power supply (400 V) and a grounded resistor (R_1, 100 kΩ) parallel with a capacitance (22 μF) were connected. Thus, the ion current signals can be detected from both the two ends of R_1 when the combustion occurs in cylinder.

3. Results and discussion

3.1. Typical ion current signal

Because of cycle-to-cycle variations in pressure and ion current signals, the average ion current and pressure of 100 cycles are used for the analysis in this paper. Fig. 3a plots the typical ion current and cylinder pressure at an ignition timing (θ_{ig}) of 22°CA BTDC, and engine speed of 2500 r/min. Fig. 3b shows the calculated average temperature and heat release during the combustion process under the same initial condition.

As shown in Fig. 3a, the ion current demonstrates two obvious stages. They are the front flame stage and the post flame stage. This is different from the three-stage ion current in previous works [24,25] where the ignition stage is presented. The possible reason is that a high-voltage silicon rectifier stack installed in front of the ion current measurement system prevents the influence of

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