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Study on the phase relation between ion current signal and combustion phase in an HCCI combustion engine

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Abstract

Ion sensing is a promising approach for cycle resolved combustion phasing in HCCI engines. This paper investigates the fundamental processes affecting the phase difference (Pdelta) between ion current signal phase Ion50 and combustion phase CA50 based on 2 numerical models. One model is used to explore fluid dynamic effects on an HCCI engine. The other model, a 10-zone model, is used to primarily explore the affecting mechanism on Pdelta. Both numerical analysis and experimental results of the ionization process indicate that Pdelta is affected by both flame ionization and fuel heat release process. For fuels with similar octane number (ON), such as gasoline (ON = 97) and ethanol (ON = 107), both the combustion phase CA50 and the ion current signal phase Ion50 retard when the equivalence ratio Φ decreases. However, the CA50 for ethanol fuel retards moderately compared with the gasoline case since the CA50 for ethanol fuel is more sensitive to intake temperature T_{in} rather than Φ. Then larger Pdelta values can be seen in ethanol fueled HCCI engine under lower Φ conditions. For the fuels with different widely octane number, such as gasoline and diesel (ON = 0), their combustion boundary conditions are different in HCCI engines, they produce ions at a different ratio. For diesel fuel, the ion production rate is much lower due to the lower intake temperature and higher compression ratio. Under low Φ conditions, the ion current signal cannot be observed at the beginning of ion concentration increase in diesel fueled HCCI engines, and the Ion50 appears much later compared with the gasoline fueled HCCI engine. As a result, the values of Pdelta increase significantly in the diesel fueled HCCI engine.

Keywords: HCCI; Combustion phase; Ion current; Flame ionization; Computational fluid dynamics

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1. Introduction

HCCI combustion concept is a promising approach with potential of very high efficiency and extremely low NO_x emissions [1]. However, combustion phasing control has been one of the

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key technological issues preventing the commercialization of HCCI combustion technology. It is generally accepted that closed-loop control (feedback control) is the key to address the phasing control issue [2,3]. In this context, a reliable and cost-effective combustion phasing control system is essential.

Piezoelectric pressure transducers are used in research engines for determination of combustion phase nowadays. However, pressure transducers are widely considered expensive and fragile for use on commercial engines. Recently, ion sensing technology has been gradually proved to be one of the alternatives to replace for combustion phasing detection in HCCI engines [4,5].

In the last decade, many experimental studies have been conducted, and the results indicated that ion sensing technology has the potential to be a robust surrogate measure of the combustion phasing since there is a correlation between ion current signal phase Ion50 (the crank angle position for the maximum ion current increasing rate), and combustion phase CA50 (the crank angle position for 50% burned mass fraction) in HCCI engines [6–8]. However, this correlation between CA50 and Ion50 is not constant and depends on the type of fuel as well as fuel–air ratio. Larsson et al. [9] show that the motion of the fuel–air mixture does not influence the phase difference between Ion50 and CA50 (henceforth: Pdelta = "phase difference between CA50 and Ion50"), but the Pdelta will be enlarged at low equivalence ratio (Φ) conditions. On the other hand, the Pdelta values are different for different fuels. Vressner et al. [8] found a maximum of 10 crank angle degrees Pdelta on a diesel fueled HCCI engine, with a much smaller phase difference for a gasoline fueled HCCI engine.

The above studies suggest that the phase difference between the combustion phase and the ion current signal can vary when the engine is operated under various load conditions or with different fuels. Succinctly, using ion current signal as a measure of combustion phase would be easy if the Pdelta were constant. However, we find changes in Pdelta that likely cannot be ignored. To address this issue, the essential mechanisms of fluid mechanics, hydrocarbon chemical kinetics, and ion chemical kinetics need a further investigation.

The flame chemi-ionization mechanism has been studied far less than non-ionic hydrocarbon combustion. Calcote et al. studied the ion formation and recombination process in flame in 1950s [10,11]. Later, the initial analysis of ion generation rates was accomplished [12,13]. For the study of soot formation processes, a mechanism for flame ionization was proposed by Warnatz et al. [14]. Based on the ionization reactions, the affecting mechanism of ion current signal amplitude variations in HCCI engines was investigated [15]. Recently, the phase-varying mechanism of the ion current signal in HCCI engines was studied, and the effect of ion producing rate on the phase Ion50 was analyzed [16]. However, the underlying reasons why these factors affect the Pdelta are not totally clear.

To achieve a consistent and reliable ion-current based combustion sensing methodology, a mechanism level understanding of Pdelta is essential. The authors exploited 2 numerical models to explore the phase relationship between the combustion phase and the ion current signal. By comparing the ion current signals in gasoline-, ethanol-, and diesel-fueled HCCI engines experimentally and numerically, the physical and chemical factors affecting Pdelta are better understood. Our research provides fundamental understanding which contributes to the improvement of ion sensing system for HCCI combustion phasing control.

2. Experimental setup

2.1. Test facility description

The specifications of the two-cylinder test engine are listed in Table 1. The displaced volume of each cylinder is 0.8 L. Intake air was heated to 468 K to trigger the HCCI combustion. The compression ratio (CR) is 12 (can be adjusted within 10–22). A 120 kW eddy current dynamometer is used to load the engine at 1400 rev/min rotation speed. A spark plug is used to detect the ion current signal. The ion sensor circuit is shown in Fig. 1. A DC bias voltage of 400 V was applied across the spark plug electrodes and a 270 kΩ resistor was used to improve the signal-to-noise ratio.

2.2. Test fuels

We investigated the factors affecting the Pdelta values in the test engine, as fueled with gasoline, ethanol and diesel. The gasoline is a Primary Reference Fuel (PRF) made up of 97% iso-octane (octane number ON = 100) and 3% *n*-heptane (ON = 0). Ethanol is pure (ON = 107), and the diesel is represented by *n*-heptane. Details of iso-octane, ethanol and *n*-heptane are in Table 2.

Table 1
Engine specifications.

Type	2-Cylinder in-line, DI
Displaced volume	800 cc
Bore × stroke	95 mm × 114 mm
Connecting rod	178.98 mm
Compression ratio	10–22
Engine speed	1400 rpm
Injector	High pressure swirl injector
Injection pressure	20 MPa
Nozzle hole number	6
Nozzle hole diameter	0.179 mm
Intake temperature	300–523 K
Head bottom	Flat