

A Study of HCCI Combustion Using Spectroscopic Measurements and Chemical Kinetic Simulations: Effects of Fuel Composition, Engine Speed and Cylinder Pressure on Low-temperature Oxidation Reactions and Autoignition

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ABSTRACT

The Homogenous Charge Compression Ignition (HCCI) engine is positioned as a next-generation internal combustion engine and has been the focus of extensive research in recent years to develop a practical system. One reason is that this new combustion system achieves lower fuel consumption and simultaneous reductions of nitrogen oxide (NO_x) and particulate matter (PM) emissions, which are major issues of internal combustion engines today. However, the characteristics of HCCI combustion can prevent suitable engine operation owing to the rapid combustion process that occurs accompanied by a steep pressure rise when the amount of fuel injected is increased to obtain higher power output. A major issue of HCCI is to control this rapid combustion so that the quantity of fuel injected can be increased for greater power. Controlling the ignition timing is also an issue because it is substantially influenced by the chemical reactions of the fuel. Various approaches are being researched for expanding the range of stable engine operation, including the application of turbocharging, the use of residual combustion gas, stratification of the fuel concentration, and the use of a blend of two types of fuel having widely different ignition characteristics.

Experiments and chemical kinetic simulations were conducted using a blended fuel of n-heptane (0 RON), which autoignites easily, and iso-octane (100 RON) that is not conducive to autoignition. The results revealed the possibility of increasing the fuel injection quantity while controlling the ignition timing. It was also found that varying the engine speed influenced the cool flame activity level, with the result that the ignition timing differed. These results provide insights for controlling the autoignition process leading to HCCI combustion.

INTRODUCTION

The Homogeneous Charge Compression Ignition (HCCI) concept has attracted widespread interest in recent years as a combustion system that achieves both high efficiency and low exhaust emissions. In the HCCI combustion process, a lean premixed mixture is compression-autoignited, making it possible to use compression ratios higher than those of gasoline engines and to reduce nitrogen oxide (NO_x) and particulate matter (PM) emissions simultaneously while providing high efficiency equal to that of diesel engines. However, it is difficult to control the ignition timing of an HCCI engine since there is no physical means of inducing ignition and combustion is initiated by compression-autoignition of the premixed mixture. Moreover, the HCCI compression-autoignition process is influenced by pre-flame reactions, referred to as low-temperature oxidation reactions, that are characteristic of this combustion system. Therefore, it is essential to have a good understanding of the autoignition process, including the various chemical reactions involved⁽¹⁾⁻⁽⁶⁾.

In this study, autoignition behavior was investigated in detail for a two-component fuel consisting of n-heptane and iso-octane, which have different ignition characteristics. That was done experimentally by making spectroscopic measurements in the combustion chamber of a test engine and analytically by conducting chemical kinetic simulations. In addition, the engine speed and cylinder pressure were also varied to examine the resultant effects on the low-temperature oxidation reactions.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

TEST ENGINE AND TEST CONDITIONS

The specifications of the test engine and the common test conditions used in all the experiments are given in Table 1. A 2-stroke air-cooled single-cylinder gasoline engine with a Schnurle scavenging system was used in the experiments. The test fuels used were the Primary Reference Fuels (PRFs) of n-heptane (0 RON), which easily autoignites, and iso-octane (100 RON) that is not conducive to autoignition. Two injectors were installed in the intake pipe to enable the flow rate of each test fuel to be controlled separately. The details of the fuel combinations used are given in Table 2.

MEASURED ITEMS AND MEASUREMENT POSITIONS

The configuration of the experimental equipment used is shown schematically in Fig. 1, and the position where the intensity of the light transmitted through the cylinder head was measured is shown in Fig. 2. Measurements were made of the cylinder pressure P (MPa), intake air temperature T_{in} (K), scavenging gas temperature T_{sc} (K), exhaust gas temperature T_{ex} (K), and the transmitted light intensity $E_{293.1}$ (V) at a light absorption wavelength of 293.1 nm, corresponding to that of formaldehyde (HCHO), a characteristic intermediate product of low-temperature oxidation reactions.⁽⁷⁾⁻⁽⁸⁾ The cylinder pressure was measured with a crystal pressure transducer installed in the top of the cylinder head. The intake air temperature, scavenging gas temperature and exhaust gas temperature were measured with K-type thermocouples installed in the intake pipe, exhaust port and the exhaust port exit, respectively.

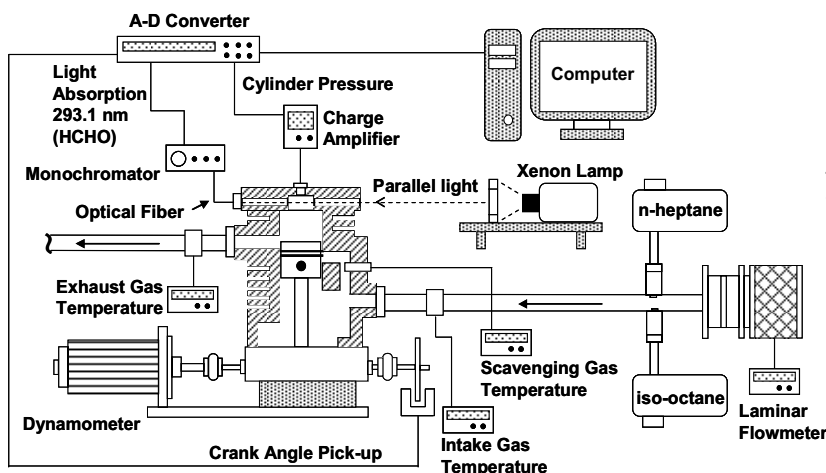


Fig. 1 Configuration of experimental equipment

Table 1 Specifications of test engine and test conditions

2 Stroke Air Cooled Single Cylinder Gasoline Engine		
Bore × Stroke	72 × 60 mm	
Displacement	244 cm ³	
Exhaust Port Closing Timing	106 deg. BTDC	
Effective Compression Ratio	$\epsilon = 10 : 1$	
Engine Speed	Standard	Ne = 800, 1000, 1200 rpm
	Numerical Analysis	Ne = 1000, 1500, 2000 rpm
Throttle	WOT	
Test Fuel	n-heptane (0 RON)	
	iso-octane (100 RON)	

Table 2 Heating value of injected fuels

Case No.	Fuel Injected Heat Value [J/cycle]			Equivalence Ratio [-]
	n-heptane, Bn	iso-octane, Bi	Total, Bt	
Case 1	330	0	330	0.5
Case 2	330	60	390	0.6
Case 3	330	120	450	0.7
Case 4	390	0	390	0.6
Case 5	450	0	450	0.7

The transmitted light intensity was obtained by irradiating the combustion chamber with parallel light from a xenon lamp through a quartz observation window (labeled “In” in Fig. 2) provided on one side of the cylinder head and sampling the transmitted light from another observation window (labeled “Out”) on the opposite side. The sampled light was passed through an optical fiber cable with a core diameter of 1 mm and introduced into a monochromator that separated it at the measured wavelength. The light at the measured wavelength was converted to an electric signal by a photomultiplier and the device’s output voltage was regarded as the transmitted light intensity. The average transmitted light intensity from the start of compression to just before the onset of the low-temperature oxidation reactions was defined as $E_{293.1(Avg)}$ (V) and the light emission intensity at any arbitrary crank angle was defined as $E_{293.1(0)}$ (V). These values were input into Eq. (1) below and converted to absorbance $A_{293.1}$. The wavelength resolution of the monochromator in terms of its half-width value was $\lambda = 4.0$ nm.

$$A_{293.1}[-] = \frac{E_{293.1(Avg)} - E_{293.1(0)}}{E_{293.1(Avg)}} \quad (1)$$

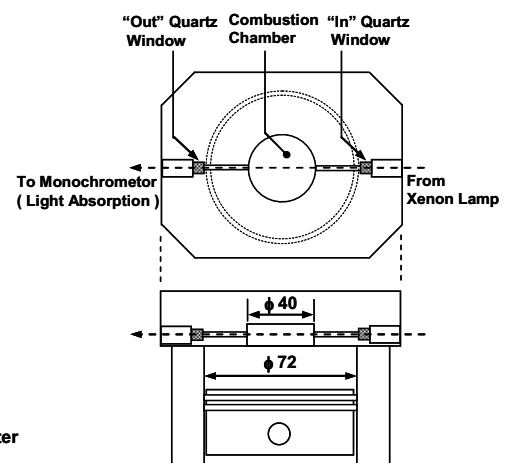


Fig. 2 Light absorbance measurement position

DEFINITIONS OF IGNITION TIMING AND TIME OF COOL FLAME OCCURRENCE

In this study, the ignition timing θ_{IT} (deg.) was defined as the crank angle at which the heat release rate (HRR) reached 10% of the maximum heat release rate HRR_{MAX} (J/deg.) of the hot flame. The time of cool flame occurrence θ_{LTR} (deg.) was defined as the crank angle at which the HRR of the cool flame reached its maximum value. These definitions are shown in Fig. 3.

CHEMICAL KINETIC SIMULATIONS

Chemical kinetic simulations were conducted using the CHEMKIN-PRO software, the IC Engine Simulator as the reactor model and the detailed reaction mechanisms of the PRFs (1,024 chemical species, 4,236 elementary reactions) in the reaction model⁽⁹⁾. In order to simulate the conditions in the combustion chamber of the test engine, the test conditions were used as the initial conditions of the simulations. However, it was not possible to reproduce the test conditions completely in the chemical kinetic simulations. The residual gas temperature in particular could not be measured in the experiments, so an initial temperature condition was defined for reproducing the ignition timing and the time of cool flame occurrence. Our calculations, assume that combustion occurs uniformly in dimensionless space and heat losses are ignored on the assumption of an adiabatic condition. For those reason, the calculations produce markedly larger values than the experimental data recorded with the test engine.

EXPERIMENTAL RESULTS AND DISCUSSION

EFFECT OF VARYING THE INJECTED FUEL QUANTITY ON COMBUSTION WHEN USING N-HEPTANE AS A SINGLE-COMPONENT FUEL

Increasing the injected fuel quantity is necessary to obtain higher engine power. Figure 4 shows the results obtained for Cases 1, 4 and 5 in which the injected quantity of n-heptane was increased while keeping the scavenging gas temperature constant at $T_{sc} = 348$ K. A close examination of the HRR waveforms in Fig. 4 reveals that the time of cool flame occurrence and the ignition timing advanced to an earlier crank angle (arrows A and B) as the injected fuel quantity was increased. The ignition timing presumably advanced because the increased quantity of n-heptane was conducive to the occurrence of autoignition. It is also seen that the maximum HRR (arrow C) and $dP/d\theta$ max rise substantially as more n-heptane was injected. Furthermore, an examination of the HCHO absorbance waveform indicates that the period from the occurrence of the cool flame to ignition was shortened as the injected fuel quantity was increased. As a result, it is seen that the ignition timing advanced to an earlier crank angle (arrows D_1 and D_2).

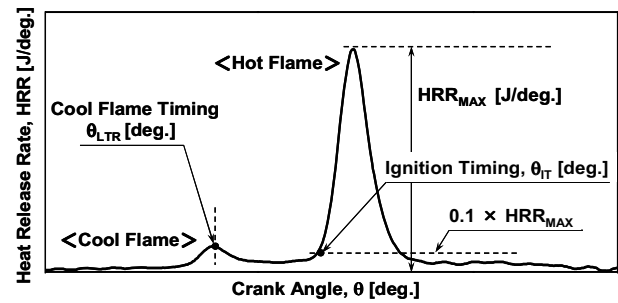


Fig. 3 Definition of ignition timing and combustion step index number

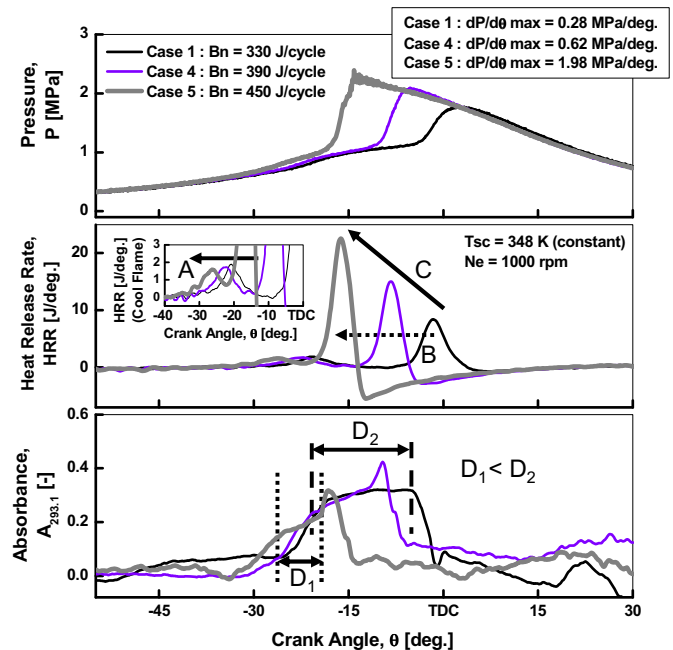


Fig. 4 Measured waveforms (Changed Bn, Constant Tsc)

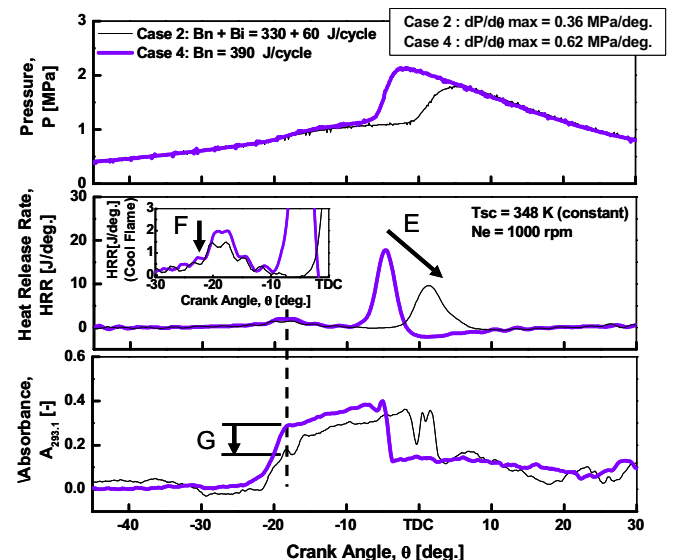


Fig. 5 Measured waveforms (Constant Bn, Constant Tsc)