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Effects of thermodynamic conditions on the end gas combustion mode associated with engine knock

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ABSTRACT

Super-knock is the main obstacle to improve power density and engine efficiency of modern gasoline engines. To understand the mechanism of super-knock, this study presents an investigation on the end gas combustion process of stoichiometric isooctane/oxygen/nitrogen mixture using a rapid compression machine (RCM), under the thermodynamic conditions close to those of production engines. The combustion process was captured by simultaneous high speed direct photography and pressure acquisition in the RCM. Three end gas combustion modes: no-auto-ignition, sequential auto-ignition, and detonation under different initial conditions were identified and characterized. The super-knock in engine was confirmed to be the result of detonation by comparing the pressure oscillation, thermodynamic state, and pressure rise relative to isochoric combustion with those of detonation observed in the RCM. The experimental results also indicate that the possibility of detonation occurrence increases with increasing initial pressure under the same compression ratio. However, comparing to the pressure, temperature has less effect on detonation formation. It was found that the end gas combustion mode is closely related to the mixture energy density. Generally, as the mixture energy density increases, the end gas combustion mode gradually transits from no-auto-ignition to sequential auto-ignition, and then to detonation. The first auto-ignition spots commonly appear in the mixture near the cylinder wall. The detonation was initiated by near-wall auto-ignition.

1. Introduction

The knock phenomenon has been an inherent problem of internal combustion (IC) engines. It is the main obstacle of applying high compression ratio to improve the thermal efficiency of gasoline engines. It is generally accepted that engine knock is associated with auto-ignition in the end gas [1]. In early times, the knock was thought by some researchers to be a result of detonation [2]. However, further investigation has substantially excluded detonation from the cause of knock due to the lack of convincing evidence. In addition, some other researchers also pointed out that detonation was unlikely to occur in naturally aspirated gasoline engines due to the low heat release rate, cool chamber wall, and short combustion duration, which could not initiate a detonation propagation [1,3].

In recent decade, high boost and direct injection hold the potential of enhancing power density and reducing fuel consumption in gasoline engines. The development, however, has been challenged by the occurrence of a new engine knock mode, called super-knock [4], mega knock [5], low-speed pre-ignition (LSPI) [6] or deto-knock [7], in highly boosted gasoline engines, especially for direct injection engines in the low-speed high-load operating regime. Super-knock can lead to very high peak pressure and pressure oscillation, in some cases, the peak pressure can reach over 300 bar and the amplitude of pressure oscillation over 100 bar [7], which could damage the engine in one engine cycle. The super-knock phenomena are significantly different from that of the conventional knock, indicating that it could have a different combustion process. Many studies have been conducted to investigate super-knock [4,5,7–24]. It is generally accepted that super-knock originates from pre-ignition. Some possible origins of pre-ignition [4,9,13,15,19,22] and the solutions to reduce the pre-ignition have also been proposed [6,16,23,24]. However, the transition from pre-ignition to super-knock and the root cause of the high pressure oscillation are still unclear.

One possibility about the super-knock occurrence is hot spot induced gaseous detonation [10]. Gu et al. [25] extended the auto-ignition theory of a hot spot, and proposed two dimensionless parameters ε (the residence time of the acoustic wave in the hot spot to the short excitation time in which most of the chemical energy is released) and ξ (the acoustic speed to the localized autoignitive

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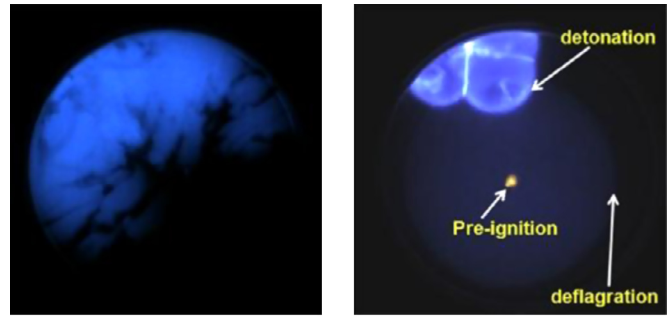
velocity). The hot spot induced combustion mode can be defined by a peninsula on ε-ξ diagram. Kalghatgi and Bradley [10] applied this method to super-knock analysis, the result showed that the super-knock cycles were located at the "developing detonation" zone in the ε-ξ diagram. However, they also pointed out that the direct propagation of detonation outside a hot spot is unlikely. In addition to the above two parameters, Rudloff et al. [12] proposed the third parameter, π (the ratio of experimental pressure rise after super-knock to the theoretical pressure rise based on isochoric combustion), to discern the super- knock. In their research, the π values of super-knock cycles were evidently higher than those of conventional knock cycles, but still less than 1, which means that the super-knock causes less pressure rise than the isochoric combustion. This can also be considered that the propagation of detonation in the combustion chamber was excluded, because according to the combustion theory, the propagating detonation should lead to much higher peak pressure than the isochoric combustion, i.e. the π should greater than 1.

Only a few super-knock related optical researches have been reported. Takeuchi et al. [18], Lauer et al. [21], and Okada et al. [13] investigated the origins of pre-ignition using endoscope. However, their results were not related to how the pre-ignition transited to super-knock. Dingle et al. [20] reported lubricant induced super-knock in an optical engine fueled with low octane number (ON) fuel (ON = 68). The high speed images showed the whole combustion process, but the frame rate (6000 fps) used in this study was too low to capture the rapid super-knock onset. In addition, the obtained images at the super-knock onset were saturated, and no useful information on super-knock onset and pressure wave propagation can be extracted. In summary, although the theoretical investigations indicate that super-knock may relate to detonation, no direct visualization of detonation combustion was observed during super-knock in optical engines.

Comparing to the optical engine, the rapid compression machine (RCM) can work under much higher pressure and provides excellent optical accessibility, which has been used in the knock related fundamental researches. Pöschl and Sattelmayer [26] investigated the influence of temperature inhomogeneity on knock using a rapid compression and expansion machine (RCEM), and observed detonation in end gas under certain conditions. However, the fuel ON is 69, which is much less than that of normal gasoline. Katsumata et al. [27] also observed detonation in the end gas and even the detonation transited from the spark triggered flame, but the test fuel was n-heptane, which ON is 0. In addition to RCM, shock tube has also been used to investigate knock related auto-ignition processes. Fieweger et al. [28] investigated iso-octane auto-ignition using high speed photography in a high pressure shock tube, and found detonation would occur when the initial temperature was over 1000 K, which is much higher than that in gasoline engines including boosted engines.

Recently, the authors carried out hundreds of RCM experiments to study iso-octane autoignition. While most of the experiments exhibited HCCI-like combustion as shown in Fig. 1(a), a few combustion processes with pre-ignition and denotation induced by unknown randomly distributed particles were observed [29]. Figure 1(b) shows the case with the pre-ignition spot located at the center of the test section. Note that the pre-ignition and super-knock were not observed in every RCM experiment, which is very similar to the sporadic characteristics of super-knock in IC engines.

There are still gaps between the above optical researches and the super-knock in production engines. Enlighten by the above randomly observed detonation process, this paper presents a systematic study of reproducing the super-knock combustion process using a spark to create pre-ignition in every RCM experiment, which allows fundamental study of deflagration to detonation under wide range of thermodynamic conditions. The end gas combustion modes under conditions relevant to the production engines were analyzed based on the high speed images, pressure traces, and the corresponding thermodynamics analyses.



(a) without pre-ignition (b) with pre-ignition [29]

Fig. 1. Combustion visualization of stoichiometric mixture compression ignition in RCM.

2. Experimental setup

2.1. Rapid compression machine

Figure 2 shows the schematic of the experimental setup. The detailed information about the RCM can be found in Ref. [30]. Briefly, the RCM has a stroke of 495 mm and a combustion chamber bore of 50.8 mm. The piston has a crevice on its skirt to reduce the temperature inhomogeneity in the combustion chamber [31] (see the enlargement of the combustion chamber in the bottom left of Fig. 2). The diameter of the inlet/outlet port is 1 mm. The dead volume generated during the machining of the port was filled with porous material to minimize gas exchange between the port and the combustion chamber.

2.2. Optical and data acquisition system

A quartz end-window was used to allow optical access to the entire combustion chamber in axial direction. The combustion images were recorded using a high speed camera (Photron SA-Z) with a 50 mm lens (Nikon Micro Nikkor 1:2.8G) at the resolution of 128 × 128 pixels, which allows the maximum frame rate of 360,000 frames per second (fps) with frame interval of 2.78 μs. For some experiments, a slightly slower frame rate (288,000 fps) with the frame interval of 3.47 μs was used. The camera shutter and lens aperture were adjusted based on the experimental conditions to avoid overexposure (image saturation) or underexposure. The acquired images were stored in 24 bit RGB bitmap format.

The pressure was measured at a sampling rate of 100 kHz using a flush mounted piezoelectric sensor (Kistler 6125C) and a charge amplifier (Kistler 5018A). The spark plug (Denso K20R) was mounted at the opposite side of the pressure sensor with electrodes located at the center of the combustion chamber. The combustion chamber pressure and the TTL pulse for spark plug and high speed camera control were acquired using a National Instrument chassis (cDAQ-9178) and an analog input module (cDAQ-9223). The spark plug and high speed camera were triggered based on the combustion chamber pressure, and the timing was controlled within 1 m/s after the end of compression.

2.3. Test conditions

This study is to investigate the super-knock under the conditions close to real engines. Therefore, pure iso-octane (>99%) was used