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An experimental investigation of super knock combustion mode using a one-dimensional constant volume bomb

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ABSTRACT

Super knock induced by pre-ignition in highly boosted spark ignition engines can cause very high peak pressure, which may lead to severe engine damage. Although it is difficult to investigate the mechanism of super-knock due to its inherent randomness, the very high peak pressure implies that super knock may relate to detonation. In this study, a tube-like one-dimensional constant volume bomb, which simplifies the geometry of a real engine's combustion chamber near top dead center, was used to better understand the fundamental phenomenon underlying super knock. H_2/O_2 mixture was used to maintain reaction intensity even at lower pressure than that in real highly boosted engines. Simultaneous high speed shadowgraphy and pressure measurement were conducted to study the effects of initial pressure and temperature on combustion mode and flame propagation. By comparing the frequencies of super knock pressure oscillation in the boosted engine and after-detonation pressure wave in the constant volume bomb, a relation can be found between the super knock and detonation. The experimental results also show that the detonation tendency of H_2/O_2 mixture in the constant volume bomb increases with increasing initial pressure but decreases with increasing initial temperature, indicating that the mixture density i.e. energy density plays an important role in detonation onset.

Introduction

Many studies have been carried out on knock phenomena using various optical methods. Most results showed that knock in spark ignition (SI) engine is a result of pressure wave oscillation caused by end gas auto-ignition and excluded detonation from the auto-ignition mode of end gas. The images captured by Konig and Sheppard [1], Spicher et al. [2], Stiebels et al. [3], and Merola et al. [4] showed that the end gas flame speed was less than the local sound speed. Kawahara

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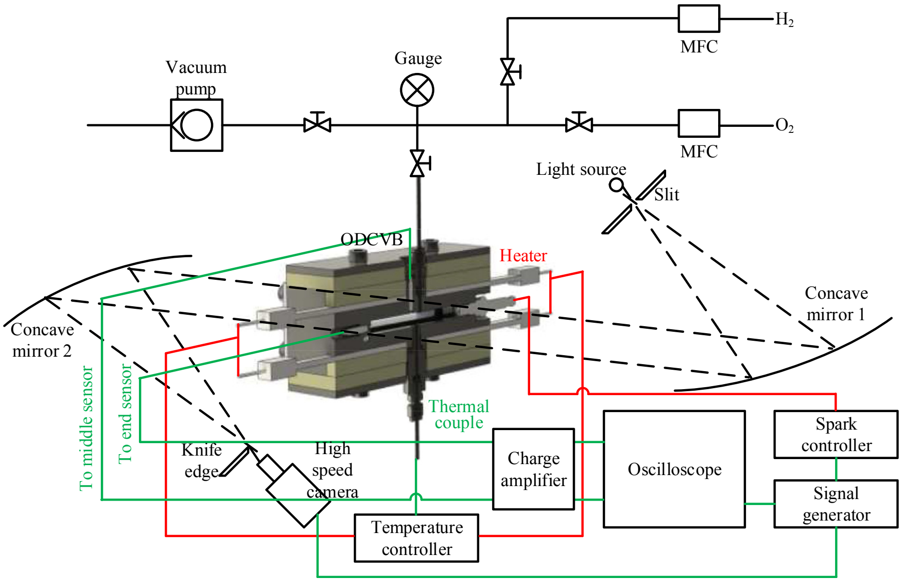

Fig. 1 – **Schematic of the experimental setup.**

and Tomita [5] visualized the pressure wave propagating away from the auto-ignition kernel and the estimated speed is 1147 m/s, which is equivalent to the local sound speed, indicating the auto-ignition mode should be deflagration. However, in another experiment conducted by Kawahara et al. [6], the results showed that a pressure wave propagating at 2085 m/s was observed. This speed is close to the detonation wave speed. As early as 1930s, Miller [7] has claimed that he observed detonation wave in an optical SI engine using a high speed camera at the speed of 200,000 frames per second (fps), but the arguments about whether the detonation can be triggered at the working conditions in SI engines still exist [28].

In recent years, pre-ignition induced super knock [8] or LSPI (low speed pre-ignition) [9] occurs in highly boosted SI engines. Although the random occurrence of super knock leads difficulties to investigate the mechanism in detail, the extremely high peak pressure caused by super knock implies that the super knock may be relevant to detonation. Kalghatgi and Bradley [8] and Rudloff et al. [10] analyzed the pressure traces using the reactivity gradient theory and deduced that pre-ignition may lead to either deflagration or detonation, depending on the thermal conditions. In their research, the super knock cycles were located in the detonation area of the regime diagram describing auto-ignition modes. Although the origin of pre-ignition have been observed by Dahnz et al. [11], Zaccardi et al. [12], Palaveev et al. [13], and Hülser et al. [14] using optical methods, there are still so far no direct visualization of how the flame or pressure wave propagates when super knock occurs.

The pre-ignition and the subsequent super knock generally occurs within ±20°CA near top dead center (TDC) [8–10,15]. During this period, the volume of the combustion chamber only changes slightly, and the process can be regarded to be isochoric. To further understand the fundamental phenomenon of super knock, a tube-like one-dimensional constant volume bomb (ODCVB) with a square cross section is developed in this study. Here, the geometry of a real engine's combustion chamber near TDC was simplified to be one-dimensional. The combustion modes under different initial pressures and temperatures are analyzed based on the recorded pressure traces and the high speed images captured using shadowgraphy.

Experimental setup

Fig. 1 shows the schematic of the experimental setup. The ODCVB has an inner cavity length of 100 mm and a cross section of 12 mm × 10 mm, which is comparable to the combustion chamber of a real engine near TDC. To visualize the flame propagation in the ODCVB, two quartz windows are used. Due to the limited size of ODCVB, the quartz window mounting slots are only 5 mm expanded from the cavity wall. This produces a sealing problem at the contact surfaces between quartz and metal in such a small dimension, especially at high pressure and high temperature conditions. To avoid leakage, the ODCVB cannot work at the same thermal conditions as in a real highly boosted engine. Therefore, H_2/O_2 (hydrogen and oxygen) mixtures are used, which are highly reactive at low pressure to simulate super knock in engines. The H_2 and O_2 are charged into the ODCVB separately, through an intake/exhaust port near the middle of the ODCVB, after the ODCVB is vacuumed and heated to the target temperature. The quantities of H_2 and O_2 are controlled based on the relative partial pressures using mass flow controller (Alicat MCQ-50sccm-D). The error of equivalence ratio, due to the existence of the dead volume of gas pipe out of the ODCVB cavity, is estimated to be less than 1%.

The ODCVB is heated by four embedded 400 W Si_3N_4 heaters. The target temperature is monitored by a thermocouple mounted in the middle of the ODCVB. The tip of the thermal couple is slightly protruded into the cavity, so that the