Fuel 144 (2015) 222–227

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Analysis of pre-ignition to super-knock: Hotspot-induced deflagration to detonation

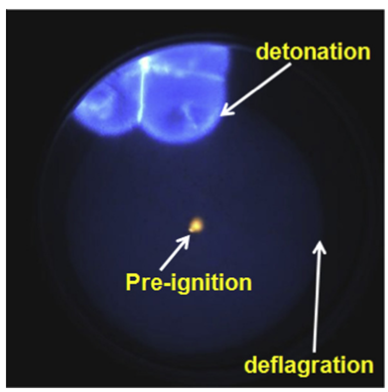
Zhi Wang [a,*], Yunliang Qi [a], Xin He [b,a], Jianxin Wang [a], Shijing Shuai [a], Chung K. Law [b,c]

[a] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China
[b] Center for Combustion Energy, Tsinghua University, Beijing 100084, China
[c] Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA

HIGHLIGHTS

- Detonation in super-knock was demonstrated for the first time by optical diagnostics.
- Pre-ignition was captured under high temperature and high pressure conditions.
- Detonation is initiated in the unburned mixture for closed system.
- High pressure oscillation induced by detonation.
- Super-knock mechanism was proposed as DDP.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 September 2014
Received in revised form 9 December 2014
Accepted 16 December 2014
Available online 26 December 2014

Keywords:
Combustion
Pre-ignition
Super-knock
Deflagration
Detonation

ABSTRACT

Occurrence of sporadic super-knock is the main obstacle in the development of advanced gasoline engines. By utilizing a rapid compression machine, events of pre-ignition and super-knock in a closed system under high temperature and high pressure were captured by synchronous high-speed direct photography and pressure measurement, with the results demonstrating that the mechanism of super-knock is constituted by hotspot-induced deflagration to detonation followed by high-pressure oscillation (DDP).

1. Introduction

High boost and direct injection holds the potential of enhanced power density and fuel consumption in the development of internal combustion engines (ICEs). Recent developments, especially in highly boosted Spark Ignition (SI), gasoline-fueled engines with direct injection in the low-speed and high-load operating regime, have however been challenged by the occurrence of a new mode of engine knock [1], which has been variously termed as super-knock, unwanted pre-ignition [2], mega knock [3], LSPI (low-speed pre-ignition) [4], Deto-knock [5], developing detonation [6,7] or subsequent front propagation [8]. It is significant to note that such a single super-knock event can instantaneously and severely

* Corresponding author at: State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62772515; fax: +86 10 62785708.

E-mail address: wangzhi@tsinghua.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.fuel.2014.12.061
0016-2361/

damage the engine due to the extremely high peak pressure and the associated pressure oscillations developed. Furthermore, super-knock events appear sporadically with little direct relationship with engine control parameters such as ignition timing, air/fuel ratio and coolant temperature. Applying the common knock suppression methods, such as retarding spark timing, enriching mixture and enhancing wall heat transfer, are not effective at suppressing the super-knock. As such, super-knock is at present the major obstacle for further improving the power density in turbo-charged SI engines.

Although numerous efforts to visualize the super-knock combustion process in ICEs have been made [9–14], no direct experimental observation has been reported that would allow quantitative analysis of a super-knock event, particularly there is no direct evidence of super-knock caused by detonation. This is because super-knock occurs at high loads, which is beyond the operating conditions of conventional optical engines. This difficulty, however, can be circumvented by using a rapid compression machine (RCM) to simulate conditions similar to those within ICEs, while providing excellent optical accessibility. Indeed, by using such a facility we have succeeded in observing, apparently for the first time, the entire super-knock combustion process, from deflagration to detonation, under high temperature and high pressure conditions, as will be analyzed in this work.

2. Experimental setup

Fig. 1 shows the schematic of the RCM experimental setup. Briefly, the RCM has a diameter of 50.8 mm and is equipped with a piezoelectric pressure transducer for pressure measurement. The data were recorded at 100 kHz using a National Instruments data acquisition system (cDAQ-9178 chassis coupled with analog input model cDAQ-9223). The RCM is equipped with a quartz optical window at the end wall, hence allowing visualization of the entire test section along its axial direction. Using a high-speed camera (Photron Fastcam SAX2, Model 1000 K) with a Nikon 50 mm lens (F1.4), color images were recorded at 45,000 frames per second with a CMOS array resolution of 512 $*$ 512 pixels, resulting in an exposure time of 23 μs. Tests using a stoichiometric iso-octane/O_2/Ar mixture were conducted under the operation conditions as listed in Table 1.

Fig. 2 shows the cross-section of the RCM combustion chamber with the passages of intake, scavenging and pressure transducer and a representative combustion image from this view.

3. Results and discussion

3.1. Combustion visualization of pre-ignition to super-knock

Fig. 3 shows a representative pressure–time history in which both pre-ignition and super-knock were observed. Note that pre-ignition and super-knock were not observed in every RCM experiment. This is similar to the sporadic characteristics of super-knock in IC engines. Hundreds of RCM experiments were carried out and most of them are homogeneous combustion. Only a few cases showed pre-ignition with the pre-ignition sites randomly distributed in the combustion chamber. For the case shown in Fig. 3, the pressure and temperature at the end of compression (time = 0) are 2.0 MPa and 932 K, respectively. The subsequent pressure development is largely similar to the super-knock trace recorded in SI engines [5], with three essential features occurring in the following sequence: (1) gradual pressure rise, indicted by a second pressure rise starting at 5.16 ms after compression; (2) strong pressure discontinuity at 6.99 ms; and (3) strong pressure oscillation, with the amplitude of the maximum pressure rise being 11.38 MPa. The knock intensity of this experiment, quantified by the amplitude of the maximum pressure oscillation (Δp), is 8.12 MPa. Since Δp of the maximum permitted knock intensity is 0.5 MPa for SI engine in general, this is a typical super-knock according to the knock intensity ($\Delta p > 5.0$ MPa) defined in Ref. [5] based on experimental data statistics and combustion parameter calculations.

These distinguishing, common features clearly demonstrate that the combustion process of the RCM experiment is fundamentally

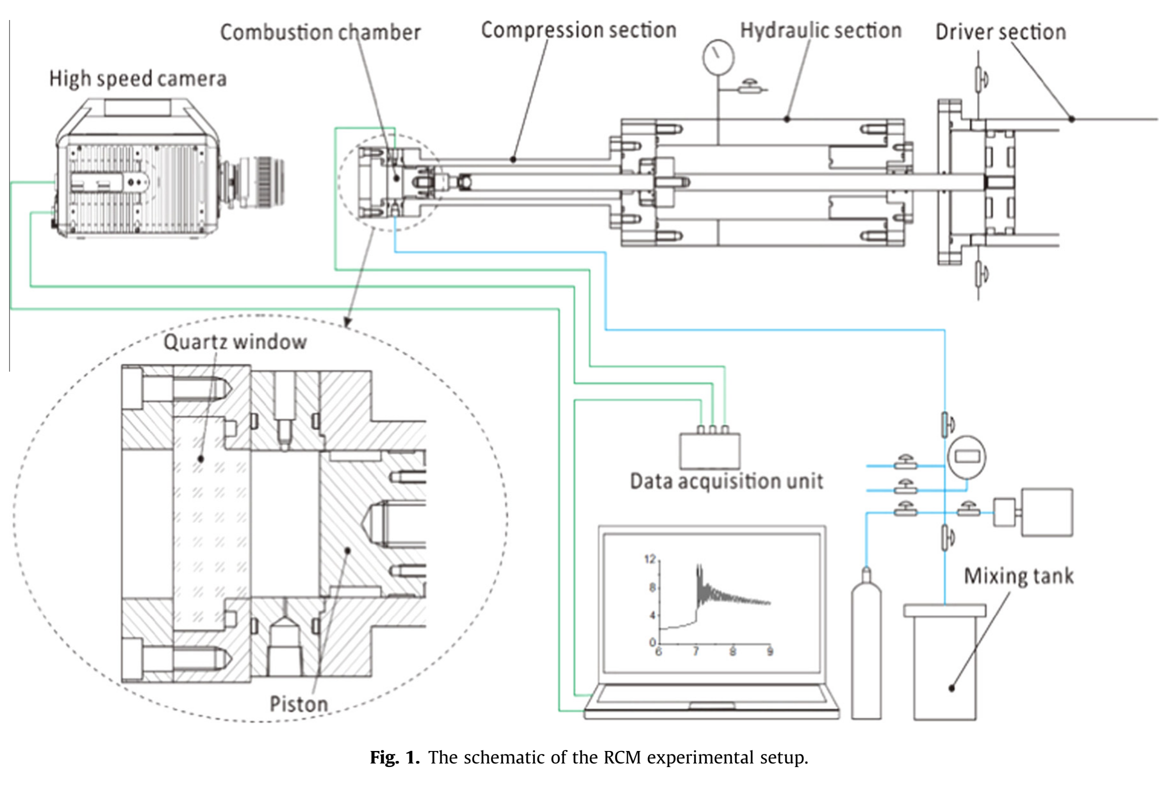


Fig. 1. The schematic of the RCM experimental setup.