Combustion and Flame 178 (2017) 277–285

Contents lists available at ScienceDirect

Combustion and Flame

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

Different combustion modes caused by flame-shock interactions in a confined chamber with a perforated plate

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ARTICLE INFO

Article history:
Received 9 April 2016
Revised 23 July 2016
Accepted 15 January 2017
Available online 7 February 2017

Keywords:
Flame-shock interaction
Autoignition
Pressure oscillation
Engine knock

ABSTRACT

The present work investigates the interaction of the turbulent flame and shock wave as well as the end-gas autoignition in a newly designed constant volume combustion chamber equipped with a perforated plate using a stoichiometric hydrogen-air mixture. Detailed high speed schlieren photography is used to track the turbulent flame fronts and shock waves which are generated by the laminar flame passing through the perforated plate. The different propagation speeds of the turbulent flames and shock waves can be obtained by controlling the initial pressures and the hole size of the perforated plate. In this work, three combustion modes were obtained clearly by experiment, depending on the interactions of the turbulent flame and shock wave, such as normal combustion, oscillating combustion and end-gas autoignition. The normal combustion is a weak turbulent flame propagation without an obvious shock wave in the confined chamber. The oscillating flame propagation is generated by the interaction of the reflected shock wave and flame front and this process can be clearly visualized in the present work. The end-gas autoignition is induced by the combined effect of the supersonic flame and the shock waves. The accelerating combustion in the confined chamber could produce the primary shock wave and the subsequent secondary shock wave is induced by the secondary flame occurring between the primary flame and primary shock wave. It is found that the secondary shock wave with speed of 780 m/s is faster than the primary one, which is the source of the end-gas autoignition. It is also observed that quasi-detonation wave produced by the end-gas autoignition can reach the speed of 1700 m/s. This wave is accompanied by a strong pressure oscillation which can explain the mechanism of engine knock.

1. Introduction

Recently the energy crisis and environmental pollution have obliged engine manufactures to realize higher thermal efficiency and lower emissions to meet stringent laws [1]. With this background, many energy-saving technologies have been put forward and as one of the most potential technologies, engine downsizing with supercharging has been followed with interest due to its significant advantages in light weight and compactness. Knock is an inherent constraint on the performance and efficiency of downsized spark ignition (SI) engines since it limits the maximum compression ratio that can be used with any given fuel [2–5]. There is no general agreement on the precise mechanism of engine knock. Two theories have been advanced to explain the origin of knock: the end-gas autoignition theory and the detonation theory [6]. It is generally agreed that knock is caused by the extremely rapid energy release of the end-gas ahead of the propagating turbulent flame, resulting in high local pressures. The irregular form of this pressure distribution causes pressure waves or shock waves to propagate across the chamber, which causes the chamber to resonate at a certain frequency. Super knock is a new engine knock mode found in downsized spark ignition engines. It can lead to a very high peak pressure (~300 bar) and pressure oscillation (~100 bar), which could damage the cylinder or piston in one engine cycle. It is generally accepted that super-knock originates from pre-ignition and is accompanied by the phenomenon of detonation [7–9]. Essentially, engine knock and super knock are always accompanied by interactions of flame and shock waves and rapid chemical energy release [10–13] or a process in which a part of or all of the charge may be consumed at extremely high rates. Thus, it is important to investigate the interactions of flame and shock waves which are the key to revealing the mechanism of knock and super knock for modern SI engines. The aim of this work is to investigate the flame-shock interactions and the pressure oscillation in a newly designed combustion chamber.

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http://dx.doi.org/10.1016/j.combustflame.2017.01.011
0010-2180/

In the literature, there are extensive fundamental studies on the interaction between flame and acoustic wave or shock wave [14–24]. The study of the flame-acoustic wave (pressure wave) interaction has made substantially contribution to understand the flame propagation and flame configuration. These studies experimentally and numerically investigated the dynamics of a distorted tulip flame or folding flame in a tube. In [18–20], the pressure wave is triggered by the contact of flame front with the lateral walls. They made the conclusion that the interaction of flame and pressure wave or acoustic wave leads to the oscillation of the flame front periodically and the different stage of flame propagation and different flame configurations. However, the pressure wave or acoustic wave cannot be directly observed experimentally. Moreover, significant progress in studying the interaction of flame and shock waves with flame acceleration using optical diagnostic techniques has been made owing to recent advances in experiment technology. It was usually investigated in an obstructed, square-cross-section channel [23–27]. In fact, the flame acceleration and propagation are also the most important stages in the interaction between the flame and shock wave for understanding pressure oscillations. A great deal of effort [25,28–32] has been spent on studying the turbulent flame acceleration mechanism in channels equipped with and without obstacles in past decades. These studies are focused on the stage of flame acceleration governed by flame-shock interaction which is an efficient way of increasing the flame energy release rate to form the detonation. However, the effect of reflected shock wave to flame propagation, end gas autoignition and violent in-cylinder pressure oscillation in confined space have not been discussed in detail.

Most recent evidence indicates that knock or super knock originates from the spontaneous ignition of one or more local regions within the end-gas. Many experiments have been made in a rapid compression machine (RCM) [33–35] as well as in an optical engine withstanding high pressure [11,12] to prove that the autoignition and detonation phenomenon is present in the end region of the chamber when knock and super knock occurs. The resulting speeds of the detonation flame in the range of 1500–2300 m/s are close to Chapman–Jouget (CJ) velocity. These results indicate that knock or super knock may be trigged by the end gas autoignition, however, during their experiments, no direct visualization of flame-shock interaction, especially turbulent flame-shock interaction, was observed clearly. And the generation process of end gas autoignition was not directly observed. In summary, the mechanism of flame-shock interaction, autoignition phenomenon as well as pressure oscillation in closed combustion chamber is not adequately understood.

The purpose of this work is to provide further understanding of the flame-shock interactions and end-gas autoignition with induced strong pressure oscillation in confined space, which also could gain an in-depth insight into the mechanism of knock formation. Therefore, a newly designed experimental apparatus equipped with a perforated plate is employed to generate the accelerated turbulent flame and shock wave in this work. The initial turbulent flame is formed rapidly as the laminar flame is passing through the perforated plate. The different propagation speed of the turbulent flame and shock wave can be obtained by controlling the initial pressure and the hole size of the perforated plate. The main new contributions of this work were the observations of three important combustion phenomena due to flame-shock interaction in confined space using newly designed experimental apparatus. And the relationship of oscillating intensities of pressure with combustion modes were well demonstrated in this work. The interaction between the flame front and shock wave is imaged by high-speed schlieren photography. The effect of the reflected shock wave on the flame front and consequently on the formation of autoignition are studied in detail. Finally, it has been observed that there are mainly three combustion modes depending on the interaction of turbulent flames and shock waves such as normal combustion, oscillating combustion and end-gas autoignition. The flame propagation velocity of high hydrocarbon fuels such as gasoline is slow and it is hard to form the shock wave by the flame across the perforated plate under present experimental conditions and the end-gas autoignition does not occur. Thus, we selected a stoichiometric H_2-air mixture as the test fuel because of its high flame propagation velocity [28,29] and the formation of the obvious shock wave ahead of the flame front, which can be used to investigate the interactions of flame-shock wave. Under certain conditions, the flame-shock interaction can generate end-gas autoignition resulting in strong pressure oscillation which is similar with what occurred in the SI engine. On the other hand, H_2-air mixture has been studied as a test fuel to study the end gas autoignition in optical engine in the work by Kawahara et al. [11,12].

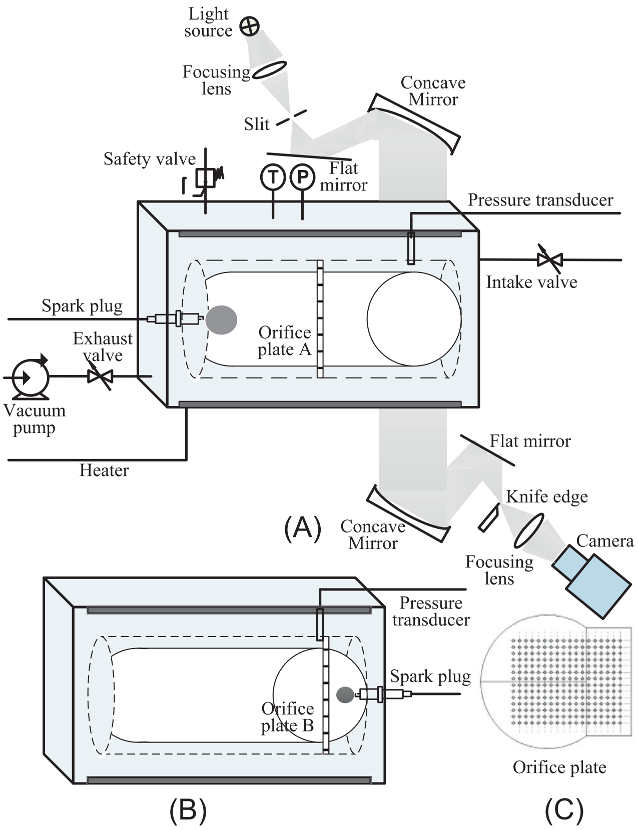

Fig. 1. Schematic diagram of the experimental setup.

The paper is organized as follows: the experimental setup and conditions are briefly discussed in Section 2. Section 3 illustrates the process of flame propagation as the flame passes through the perforated plate. The results and discussion are presented in Section 4, involving the three different combustion modes of normal combustion, oscillating combustion and end-gas autoignition as well as the analysis of pressure oscillations. Finally, major conclusions from this work are drawn in the last section.

2. Experimental setup and conditions

Experiments were carried out in a newly designed constant volume combustion bomb equipped with a high-speed schlieren photography system, as shown in Fig. 1. The entire experimental system consists of a constant volume combustion chamber, a high-speed schlieren photography system, a pressure recording system, a temperature control system, an intake and exhaust system, a