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Effects of the equivalence ratio on turbulent flame–shock interactions in a confined space

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ABSTRACT

In this work, the influences of the equivalence ratio on flame front propagation velocity, shock wave velocity and pressure oscillation as well as flame–shock interactions with different combustion phenomena were comprehensively studied experimentally in a newly designed constant volume combustion bomb (CVCB). And a hydrogen–air mixture was chosen as the test fuel. In the CVCB, an orifice plate was used to obtain flame acceleration and promote turbulent flame formation. High-speed Schlieren photography was employed to capture the turbulent flame front and shock wave in the present work. The evolution of the flame and shock wave together with influences of the equivalence ratio on the flame tip velocity, shock wave velocity and pressure oscillation were clearly presented. The results showed that, after the laminar flame passed through the orifice plate, wrinkled turbulent flame gradually formed, and the shock wave ahead of flame front could be seen at a certain condition. The shock wave formation and enhancement process induced by flame acceleration was clearly captured by the Schlieren photography. It was found that the mean turbulent flame tip velocity reached a maximum value at an equivalence ratio of 1.25. In addition, an increase in the initial ambient pressure resulted in an increase of the turbulent flame tip velocity. Forced by the flame–shock/acoustic interactions, the flame would reverse and the backward flame velocity was positively related to that of the forward flame. The forward shock wave showed little differences among different equivalence ratios, while the reflected shock decayed fastest for the fastest flame, and the turbulent flame was pushed back more apparently. And the effect of the equivalence ratio on the pressure oscillation caused by flame acceleration and flame–shock interactions in the end gas region of confined space was determined.

1. Introduction

Efficient vehicle technology, such as turbocharging and downsizing of an engine and gasoline direct injection (GDI), plays a significant role in solving the transportation problems of air pollution, energy insecurity and climate change [1]. However, the thermal efficiency of GDI turbocharged and downsized spark ignition (SI) engine is still far below that of a diesel engine and is constrained by knock, which limits the maximum compression ratio of engine [2–5]. When knock occurs, the in-cylinder pressure oscillates in high amplitude over 0.5 MPa and is accompanied by knocking noise, thereby deteriorating the engine performance and damaging the engine components. There are two generally accepted theories explaining the mechanism of knock, including auto-ignition theory and detonation theory [6]. The auto-ignition theory assumes that engine knock is the result of auto-ignition in the end-gas before it is reached by the flame front emanating from the spark plug. After spark ignition, the unburned mixture is compressed by the expanding burned mixture and heated by the radiation from the flame front. Once the temperature and pressure of the end gas meet the requirements of its auto-ignition, the end gas ignites spontaneously, starting at one or more points. Subsequently, a violent explosion occurs in the end gas, causing pressure wave oscillation in the combustion chamber [7–9]. Nevertheless, detonation theory assumes that knock occurs because of the propagation of the flame front that accelerates from the spark plug to the end of the detonation. The shock wave then reflects from one cylinder wall to another at the combustion chamber. The impact pressures are short in duration but high in magnitude, inducing the occurrence of knock [10]. Essentially, both auto-ignition and detonation combustion modes are relevant to flame–shock interactions and pressure oscillation [11–13]. Understanding the flame–shock interactions and pressure oscillation in confined space not only is of fundamental significance but also commands practical interest, such as understanding the mechanism, prediction and suppression of knock.

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Flame acceleration and interactions between flame and acoustic or shock wave have been widely studied through experiments or simulations [14–21]. In most of the research studies, smooth ducts and obstructed ducts were mainly used to accelerate the flame and induce the acoustic or shock wave even denotation. Different flame acceleration mechanisms were demonstrated in smooth and obstructed tubes [22–28]. The study of the flame–acoustic or shock wave interaction has made substantial contributions to understand the flame propagation and flame configuration [29,30], in which more interesting topic is the flame–acoustic resonance in a tube. Petchenko et al. [31] presented flame propagates in a tube with a closed end by direct numerical simulation, and found that acoustic wave oscillations produce a strongly corrugated flame front induced to a strong Rayleigh–Taylor (RT) instability. Xiao et al. [32] experimentally demonstrated the periodical interaction of the flame with the pressure wave because of the contact of flame front with the lateral walls. The interactions between flame and acoustic or shock wave are involved with the various flame instabilities [33,34]. Apart from Kelvin–Helmholtz (KH) instability mechanism for the interface between the flame and shock wave, the flame–shock wave interaction will distort the flame front and increases the energy release rate in the combustion system according to Richtmyer–Meshkov (RM) instability, which plays an important role in the deflagration to detonation transition. However, the impacts of the flame–shock interactions on the turbulent flame propagation and pressure oscillation in the end of the confined combustion chamber have not been investigated in detail.

The equivalence ratio is one of the most important factors in the combustion process, significantly influencing the flame propagation, in-cylinder pressure and so on. An effective method to reduce knocking tendency is to control the equivalence ratio of fuel–air mixture. Therefore, it is important to understand the process of flame propagation and pressure oscillation at different equivalence ratios in a confined combustion chamber. In the literature, extensive fundamental studies exist on the influences of equivalence ratio on the flame propagation [35–37], especially the laminar flame speed. These studies found that the laminar flame speed of hydrogen–air mixture varied with the equivalence ratio non-monotonously and reached the peak point at the equivalence ratio of approximately 1.6 at the standard pressure and atmospheric temperature. However, the effect of the equivalence ratio on the turbulent flame propagation velocity of the hydrogen–air mixture is not well understood, specifically in a confined space. In the present work, the turbulent flame propagation characteristics as well as flame–acoustic or shock wave interactions with pressure oscillation at different equivalence ratios in a confined space have been studied comprehensively, which may be of great significance in combustion science and will be studied here.

The major objective of the present work was to experimentally investigate the influences of the equivalence ratio on the propagation of turbulent flame and shock wave, as well as their interactions. The experimental study was conducted in a newly designed constant volume combustion bomb (CVCB) with an orifice plate. In the CVCB, the orifice plate was used to achieve the flame acceleration and produce turbulent flame and shock waves at different levels. High-speed Schlieren photography was employed to capture the flame front and the shock wave in the present work. A hydrogen–air mixture was chosen as the test fuel because of its fast flame propagation velocity and the ease to form a shock wave ahead of the flame front. Moreover, the combustion phenomena of the hydrogen–air mixture are important because of its clean combustion character as a renewable fuel and because they are the fundamental oxidation mechanism for complex fuels [38]. The present work demonstrates the following new contributions according to authors' knowledge: (1) the physical phenomenon of shock wave formation and enhancement induced by accelerating turbulent flame propagation, (2) the mechanism of turbulent flame and the shock wave propagations at different equivalence ratios in a confined space, (3) the effects of the turbulent flame and shock wave propagations at different equivalence ratios on the pressure oscillations, (4) the effects of equivalence ratios on the interaction mechanism of flame–shock/acoustic involving the velocities of flame and reflected shock wave with different combustion phenomena. This study might provide a new insight into the turbulent flame–shock interactions and the mechanism of knock in a confined space.

The paper is organized as follows: the experimental apparatus and procedure are briefly discussed in Section 2. The process of flame acceleration and propagation after the orifice plate and the mechanism of shock wave formation are shown in Section 3. The results and discussion are presented in Section 4. Finally, major conclusions from this work are presented in the last section.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

Experiments were conducted using the constant volume combustion bomb (CVCB) apparatus outlined schematically in Fig. 1. In this study, two arrangements of the experimental apparatus was applied for different purposes shown in Figs. 1(a) and 2(b), respectively. The detailed explanation about these two different arrangements was shown in Section 2.3. This experimental apparatus was comprised of the following: constant volume combustion bomb, orifice plate, intake and exhaust pipe system, ignition system, heating system, image acquisition system, pressure acquisition system and time synchronizing system.

The combustion chamber was comprised of a 100-mm diameter and 230-mm long cylinder with a total volume of 2.32 L. In addition, the combustion chamber was capable of withstanding a maximum transient pressure of 10 MPa. As a precaution, a safety valve with limit pressure of 8 MPa was installed. There were two pieces of optical glass mounted facing each other, one at the front side and the other at the back side of the CVCB. The windows were made of high-quality quartz glass, which provided optical access, with a thickness of 100 mm and 50 mm for the front and back, respectively. The front window was in a racetrack shape of 230 mm in length and 80 mm in width, and the back window was in a circular shape of 80 mm in diameter. The orifice plate was made of a 3-mm thick stainless steel plate. There were several holes on it, depending on the porosity, distributed in rectangular form. The Bosch R6 spark plug was employed to ignite the mixture, which could generate a spark with duration of 0.7 ms. A cluster of electric heating units with total power of 2 kW was used to heat the whole CVCB equably. The bomb temperature was controlled using a closed-loop feedback controller with an uncertainty less than 3 K. This would prevent combustion products condensing into droplets. The combustion images were recorded by the image acquisition system using high-speed Schlieren photography technology at the frame rate of 90,000 fps and exposure time of 1 μs. The pressure acquisition system was utilized to capture the in-cylinder pressure at a sampling rate of 100,000 Hz via a piezoelectric transducer (Kistler 6113B) installed on the top of the combustion chamber 30 mm away from the right wall. The time synchronizing system was used to guarantee that the image acquisition system, the pressure acquisition system and ignition system began to operate simultaneously.

2.2. Experimental procedures

Before setting up the experiment, the combustion chamber was heated to the objective temperature by the heating system.