Combustion and Flame 190 (2018) 216–223

Contents lists available at ScienceDirect

Combustion and Flame

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

Flame propagation and combustion modes in end-gas region of confined space

Lei Zhou, Lijia Zhong, Jianfu Zhao, Dongzhi Gao, Haiqiao Wei*

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 15 August 2017
Revised 21 October 2017
Accepted 8 December 2017

Keywords:
Flame propagation
Combustion mode
Confined space
Shock wave

ABSTRACT

Flame propagation is investigated in a designed experimental apparatus equipped with a perforated plate in a constant volume chamber. The effect of the perforated plate is to generate a rapidly accelerating flame based on Bychkov work (Bychkov et al. 2008), in which the flame across the obstacle will becomes a strong jet flame. The experiment was conducted with a hydrogen–air mixture at different conditions. In this work, six different turbulent flame propagation and combustion modes were clearly observed at various conditions in our designed experiment. In the presence of perforated plate, the turbulent flame formed through the perforated plate may perform six types of turbulent propagations at the end gas regime. These types form through the interaction between the flame and the shock or acoustic wave and because of the limited effect of the wall in confined space. The six forms are as follows: (1) a normal flame propagation with a low flame front tip velocity and combustion rate; (2) a weak pulsation propagation with weak fluctuation due to the acoustic wave; (3) a pulsation propagation only with a visible reflected shock wave; (4) a strong pulsation propagation with a forward shock wave and shock reflection; (5) a continuously accelerating flame propagation due to auto-ignition of the unburned mixture between flame front and shock wave, which also leads to strong pressure oscillation; and (6) a violent pulsation propagation with a multi-shock wave leading to end gas auto-ignition with large pressure oscillation.

1. Background and introduction

Turbulent flame is one of the most interesting parts of combustion physics and turbulence research as evidenced by analytical, experimental and computational studies in the past few decades [1–8]. Much detail can be found in comprehensive reviews on turbulent and other types of flames [9–12]. For example, some of these studies examined the turbulent premixed flame speed in a nearly constant-pressure apparatus with fans, which presented the self-similar propagation of a turbulent flame [6,13,14]. In other studies [15–19], they showed that turbulence corrugates the flame front by increasing the burning rate and facilitating flame acceleration, which boosts the process of deflagration to detonation transition (DDT).

Of particular interest is turbulent flame acceleration and propagation in confined space. As turbulent combustion in confined space, i.e., confinement, occurs, flame acceleration and expanding propagation will generates a series of compression waves with considerable amplitude. In turn, confinement significantly influences the turbulent flame brush and wrinkles it. Therefore, in flame propagation the flame–shock/acoustic interactions play a vital role and finally determine the turbulent flame development and combustion phenomena. Understanding the turbulent flame propagation mechanism involving flame–shock/acoustic interaction in confined space not only is of fundamental significance but also contributes to practical applications such as spark-ignition engines with knock phenomenon and explosion hazards in coal mine fields.

There have been some attempts to explain flame acceleration and flame–shock/acoustic wave interactions. Of course, flame acceleration is strongly relevant to flame–shock/acoustic interactions. Based on previous explanations, there are four primary aspects to flame acceleration and flame-shock/acoustic interactions: 1) flame self-acceleration for expanding spherical flame, 2) flame acceleration mechanisms in DDT, and 3) flame–acoustic interaction, 4) flame–shock interaction.

Law and co-workers [6] comprehensively investigated the turbulent flame acceleration mechanism for a spherical flame in a constant pressure vessel. They found the normalized turbulent flame speed as a function of length scale and transport property, which demonstrates flame self-similar propagation. After, they clarified the scaling of turbulent flame speed with Markstein diffusion consideration [16]. Kim et al. [20] also presented the

---

* Corresponding author.
E-mail address: whq@tju.edu.cn (H. Wei).

https://doi.org/10.1016/j.combustflame.2017.12.007
0010-2180/

self-similar propagation in large scale gas explosions. Bradley et al. [21] have also made much contributions for the turbulent flame burning velocity. In past decades, a great deal of effort [1,2,22–27] has also been spent on studying the turbulent flame acceleration mechanism for DDT in channels equipped with and without obstacles. Recently, Dorofeev [2] reviewed the underlying mechanism and physical phenomena of flame acceleration in different configurations. Compared to flame propagation in smooth tubes, flame in obstructed tubes with obstacles is easier to convert into a turbulent flame. They demonstrated different flame acceleration mechanisms, in which Shelkin mechanism [28] and Bychkov theory [29] are the most popular and well-known.

When burning occurs in confined space, a flame will produce a series of acoustic waves. The study of flame–acoustic wave (pressure wave) interactions has made substantial contributions to understanding flame propagation and flame configuration [25,30–33], in which a more interesting topic is the flame-acoustic resonance in a tube. In a simple tube without obstacle, Petchenko et al. [30] presented flame propagation in a tube with a closed end by direct numerical simulation. As a result, acoustic oscillations produce an strongly corrugated flame front induced by strong Rayleigh–Taylor(RT) instability. Akkerman and Law [13] developed a quasi-1D model to study the effect of acoustic coupling on power-law flame acceleration in spherical confinement. The acoustic interact with the flame front finally affected the flame morphology and propagation speed. Xiao et al. [25] experimentally demonstrated the periodical interaction of the flame with the pressure wave because of the contact of the flame front with the lateral walls. When the acoustic or compression waves coalesce ahead of the flame to form a stronger compression wave, a leading shock wave is formed. Apart from the Kelvin–Helmholtz instability mechanism for the interface between the flame and the shock wave, flame–shock wave interactions distort the flame front and increases the energy release rate in the combustion system according to the Richtmyer–Meshkov (RM) instability [34], which plays a key role in the DDT.

In fact, for flame propagation in tube, five stages of flame dynamics can be distinguished based on the classical tulip flame propagation [35–37]. However, the combustion modes of turbulent flame dynamics in confined space have not yet been clearly demonstrated in previous studies. Additionally, the effect of flame-shock/acoustic interactions on the flame propagation and combustion modes with pressure oscillation has not yet been comprehensively studied.

Therefore, the objective of this seminal work is to experimentally and clearly reveal the possibility modes of flame propagation and combustion phenomena in confined space for the first time. The experiment was carried out by our designed experimental apparatus equipped with a perforated plate. A hydrogen–air mixture was chosen as the test fuel because of its fast flame propagation velocity and its clean combustion character as a renewable fuel. In this work, the effect of the perforated plate is to generate a rapidly accelerating flame based on Bychkov work [29] and a wrinkled flame due to RT instability.

The paper is organized as follows: the experimental setup and conditions are briefly discussed in Section 2; flame propagation and combustion modes are presented in Section 3; and finally, main findings from this work are drawn in the last section.

2. Experiment setup

This experiment was carried out in a newly designed constant volume combustion bomb (CVCB) equipped with a high-speed Schlieren photography system, as shown in Fig. 1. The entire experimental system consisted of a constant volume combustion chamber, a high-speed Schlieren photography system, a pressure recording system, an intake and exhaust system, a high-voltage ignition system, perforated plates with different aperture sizes and a synchronization controller. The combustion chamber was a closed cylindrical cavity with an inner diameter of 100 mm and length of 230 mm. The entire vessel was uniformly preheated by a set of electrical heating elements with a power rating of 2 kW. The interior air temperature was set to 353 K and controlled within 3 K using a closed-loop feedback controller. The pressure rise during the combustion process was recorded using a Kistler 6113B pressure transducer at 100 kHz. In this experiment, hydrogen is selected as a fuel. And according to the Dalton partial pressure law, the quantity of hydrogen and air was defined in terms of the pressure at different equivalence ratios. Prior ignition, the fuel and the air mixture were initially premixed for 5 min to realize homogeneous mixture without gas flow effect. The mixture was ignited using a slightly modified standard ignition plug with extended electrodes. The ignition system generated a spark with duration of 0.7 ms and the timing was synchronized with the interior pressure rise recording. For safety reasons, an 8 MPa pressure release valve was installed in the combustion vessel. Replaceable perforated plates with different aperture sizes of 1.5 mm, 2.5 mm, and 3 mm were installed at the middle (A) distance from the left wall to generate turbulent flames with different intensities. The perforated plate was made using a 3 mm thick stainless steel plate. There were several 2 mm diameter through-holes on it, distributed in rectangular form (18 rows, 14 columns) as shown in Fig. 1 and in this work the number of holes remains constant. The porosity (or void fraction) in present work indicates a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100%.

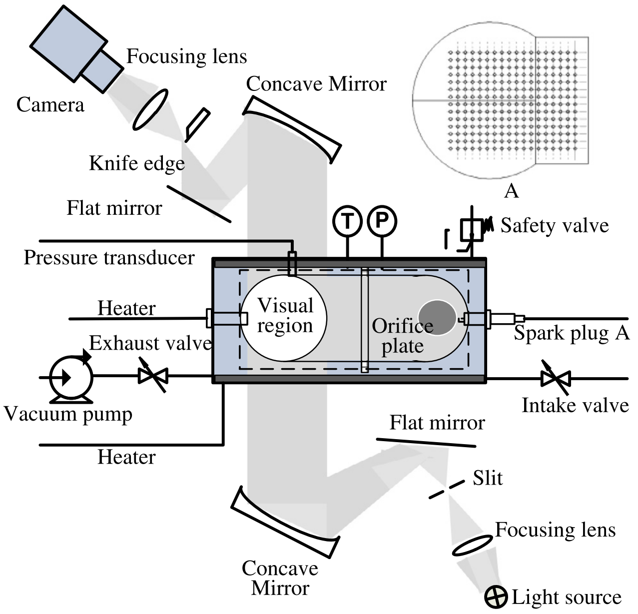

Fig. 1. Experimental apparatus.

At the end of the chamber, there is a heating rod with a diameter of 10 mm to heat the mixture at the end. However, in this work the heating rod was not used. Instead of the heating rod at the same position, the second spark plug was used to ignite the end mixture. The test conditions involving initial ambient temperature, ambient pressure, equivalence ratio, hole size and porosity are shown in Table 1. Because the focus of this work is to demonstrate the potential combustion modes in confined space, the present cases are chosen to represent all the possible combustion modes. A 240 W lamp is used as the light source. The light is focused onto a slit using a focusing lens to generate the spotlight for the Schlieren technique. Passing through a group of mirrors, the