Available online at www.sciencedirect.com

ScienceDirect

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

Experimental study of flame propagation across a perforated plate

Quan Li [a], Xuxu Sun [a], Shouxiang Lu [a,*], Zhi Zhang [b], Xing Wang [b], Sen Han [b], Changjian Wang [b,**]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, PR China
[b] School of Civil Engineering, Hefei University of Technology, Hefei, 230009, PR China

ARTICLE INFO

Article history:
Received 14 January 2018
Received in revised form
10 March 2018
Accepted 12 March 2018
Available online xxx

Keywords:
Hydrogen safety
Flame propagation
Perforated plate
Secondary flame front

ABSTRACT

Flame propagation across a single perforated plate was experimentally studied in a square cross-section channel. Experiments were performed in premixed hydrogen-air mixture with different equivalence ratios and initial pressures, aiming at identifying the parametric influence. High-speed schlieren photography and pressure records were used to capture the flame front and obtain the pressure build-up. Four stages for the flame front crossing the perforated plate were obtained, namely, laminar flame, jet flame, turbulent flame and secondary flame front. Following ignition, a laminar flame was obtained, which was nearly not affected by the confinement. This laminar flame was squeezed to pass through the perforated plate, producing the jet flame with a step change on velocity. Turbulent flame was generated by merging the jets, which facilitated the acceleration of the flame front. Secondary flame front induced by Rayleigh-Taylor instability was clearly observed in the process of the turbulent front moving forward. Both velocity and pressure are enhanced in this stage. Parametric studies suggested that the secondary flame front is more obvious in the stoichiometric mixture with higher initial pressure, and characterized by a faster propagation velocity and a bigger pressure rise.

Introduction

Energy crisis and environmental issues associated with use of fossil fuels for transportation has stimulated great interest in pursuing a high efficiency dedicated engine with hydrogen-based fuels to cut greenhouse gas exhaust [1]. Therefore, hydrogen as the alternative fuels will likely be the mainstream of World's transportation fleet for a very long time [2]. The safety issue during exploitation, storage and utilization of hydrogen is once again at the forefront. This is due to the unique properties of hydrogen, such as a wider flammability range, lower ignition energy and greater propensity to leak. Any accidental release of hydrogen into a confined space may pose an explosion hazard. Generally, explosion involves a laminar flame and the following self-acceleration by inducing flow instabilities (thermal-diffusion, Landau-Darrieus (LD), Kelvin-Helmholtz (KH), Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) etc). So gaining an understanding of flame acceleration in a confined space is of fundamental significance both in terms of industrial safety [1] and engineering applications.

Flame acceleration has been widely studied in obstacle-free or obstacle-laden tubes and different mechanisms for

* Corresponding author.
** Corresponding author.
E-mail addresses: sxlu@ustc.edu.cn (S. Lu), chjwang@hfut.edu.cn (C. Wang).
https://doi.org/10.1016/j.ijhydene.2018.03.079
0360-3199/

Please cite this article in press as: Li Q, et al., Experimental study of flame propagation across a perforated plate, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.03.079

flame acceleration were demonstrated. Following ignition, a laminar flame is initiated, which propagates as a curve front rather than a stable planar front [3–5] due to the hydrodynamic instabilities. "Tulip flame", as one of most interesting phenomena, was observed in the experiments of premixed flame propagating in smooth tubes. Various possible explanations have been suggested, i.e., LD instability, vortex motion just behind flame front and flame-acoustic (pressure) waves interaction, among which the last is the most interesting. Pressure waves can be generated by the moving flame front. Xiao et al. [6] numerically demonstrated that the coupling effect of the pressure waves and the flame causes a drastic flame and pressure oscillations. Acoustic fluctuations in the combustion zone cause more unsteady heat release [7].

The most important effect of obstacles on flame propagation, compared to that in a smooth tube, induces turbulence by distorting the unburned gas flow field and therefore resulting flame area enhancement (flame folding) [8]. Shelkin [9] qualitatively attributed flame acceleration to wall friction and turbulence. Turbulence, however, is far from being well understood yet despite a century of intensive study [10]. Generally, the propagating flame over the obstacles results in the generation of KH instability that shears the flame. The propagating flame also creates a recirculation zone downstream of each obstacle which is separated from the main flow by a turbulent shear layer [11]. The flame tip is subjected to RT instability when it accelerates across the obstacles. This instability is originated when a lighter fluid (burned products) is accelerated towards a heavier fluid (unburned gas). Tsuruda and Hirano [12] observed that turbulence induced by RT instability at the flame leading front causes the flame front itself to become of a needle-like structure (secondary flame front). Acoustic wave-flame interaction, as mentioned above, continues to play a role on turbulence generation. Turbulence, within the flame and flow region, enhances transport of heat and mass and distorts the flame surface, resulting in a higher burning rates. The turbulence burning rate can be facilitated to reach 10 times that of the laminar burning rates. In Bychkov et al.'s [10] theory, the delayed burning between the obstacles creates a powerful jet-flow driving the acceleration, whereas, turbulence plays only a supplementary role.

Turbulence is induced by placing solid objects, such as rings, wall baffles, Schelkin spirals and perforated plate, in the flame path. Perforated plate gains in-depth researches due to both the flame accelerating effect and the quenching effect as flame arrestors. For propagating flame, Pinaev [13] found that the flame propagating in porous media at velocity larger than 5 m/s produces a local pressure rise just ahead of the flame front. Flow field is greatly perturbed by perforated plates along the flame path. Based on this, Fortin et al. [14] adopted the perforated plate to obtain a stable detonation in a very short distance. Recently, a set of works had been done in a combustion bomb with a perforated plate to study turbulent flame-shock interaction by Wei et al. [15–17]. The process of flame propagation through the perforated plate can be characterized by three stages: laminar flame, jet flame and turbulent flame. Also, perforated plates, extracting thermal energy from the flame resulting in flame quench, are commonly used in the chemical industry to prevent accidental combustible mixture ignition to a violent explosion [18]. Jarosinski et al. [19] proposed that so called quenching distance or even the minimum orifice size can be evaluated based on critical Peclet number Pe $\approx$ 42. Wang and Wen [20] numerically suggested that the perforated plate has an effect on the flame tip speed downstream of it.

In most perforated plate flame studies, very little attention was given to flame acceleration mechanisms and parametric studies. The major objective of the present study was to experimentally investigate the phenomenon of the flame tip crossing the perforated plate and its underlying mechanism. Also, parametric studies will be carried out to investigate equivalence ratios and initial pressures effects on flame evolution. Such study promotes our better understanding of the flame acceleration mechanism of perforated plate.

Experimental apparatus

Experiments were conducted in a closed square tube with a 7 × 7 cm cross-section, composed of one optical segment and one non-optical segment, as shown in Fig. 1. Each segment had an identical length of 50 cm. The optical segment was embedded by two quartz glass window, having the distance of 9 cm from the point of ignition, to provide a 23.5 × 7 cm field-of-view to visualize flame tip evolution. The visualization was achieved by a single-pass schlieren system with a NAC HX-3E high-speed camera with a shutter speed of 19.9 μs and 30,000 frames per second. The perforated plate with a 6.9 × 6.9 cm cross-section and a 2.0 cm thickness was installed 7 cm away from the left-end of the field-of-view. There was 196 holes in it with holes' diameter of 2 mm, disturbed in a matrix structure (14 rows, 14 columns). Three PCB piezoelectric pressure transducers (model 102B16) were employed to measure the pressure at different axial positions near the perforated plate. Each pressure transducer (PT) was spaced 100 mm apart, and PT1 was located 110 mm away from the ignition-end. Combustion was initiated by a spark plug connected to an automotive capacitor discharge system. The spark plug was installed on the left-end of the optical segment.

The gaseous mixture is initially produced at a pressure of 300 kPa in a separate mixing chamber, for multiple tests. Once the mixing chamber pressure drops below 100 kPa, a new mixture is prepared in order to ensure no ambient air introduced into the mixing chamber. Prior to each shot, the combustion channel was first evacuated, ensuring that then early vacuum state can be kept with the leakage less than 10 Pa in at least 30 min, and then loaded with the mixture at the desired initial pressure. Tests were performed at an initial pressure in the range of 40–100 kPa with equivalence ratio (Φ) between 0.6 and 3.0.

Results and discussion

The process of flame acceleration passing through the perforated plate

To understand the process of flame acceleration crossing the perforated plate, typical schlieren images at $P_0 = 80$ kPa and $\Phi = 1.6$ are presented in Fig. 2, as well as the flame tip velocity

Please cite this article in press as: Li Q, et al., Experimental study of flame propagation across a perforated plate, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.03.079