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A comparative study on premixed hydrogen–air and propane–air flame propagations with tulip distortion in a closed duct

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HIGHLIGHTS

- The distorted tulip shape was for the first time found in premixed propane–air flame.
- The tulip distortions are always accompanied by flame tip velocity fluctuations.
- The pressure dynamics is different for premixed hydrogen–air and propane–air flames with tulip distortion.
- Pressure wave effect is not the incitation factor of tulip distortion.

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ABSTRACT

The premixed hydrogen–air and propane–air flames in a closed duct were experimentally studied for a deep insight into the tulip distortion phenomenon. High speed schlieren photography and pressure sensors recorded the flame images and pressure dynamics at different equivalence ratios for detailed analyses and comparisons. The distorted tulip shape which was first scrutinized and distinguished as an exclusive feature in premixed hydrogen–air flame, was also observed in stoichiometric premixed propane–air flame with a similar behavior on flame shape changes. Tulip distortions are always accompanied by remarkable flame tip velocity fluctuations with near-constant amplitudes. But the pressure dynamics is totally different. There are no observable oscillation and stepped rise in pressure trajectory of stoichiometric premixed propane–air flame. The pressure wave effect is definitely not the incitation factor, but an additional enhancement of flame acceleration, deceleration and deformation.

1. Introduction

Premixed flames in closed ducts are of great interest and importance in combustion frontier research for more detailed knowledge of internal combustion engines, early buildup of detonation, safety issues in production, storage, transportation and powertrain [1–7].

During the propagation in the closed duct, premixed flame is affected by a combined effect from body force, hydrodynamic instability, diffusive-thermal instability, boundary layer, etc., which makes it unstable and irregular [8–12]. As demonstrated by photographic techniques, the flame indeed undergoes complex shape changes. Among all these shapes, the most interesting and attractive one is tulip flame (named by Salamandra et al. [13]). Ellis [14] captured this phenomenon for the first time, who found that flame shape changed suddenly from a forward pointing finger to a backward pointing cusp at the last stage of combustion in closed tubes with sufficiently high aspect ratio (>2). Since then, tulip flame dynamics has been extensively studied for years [15–17]. Besides experiments, numerical and analytical methods were also developed for reproducing the phenomenon and helping reveal the underlying mechanism [18–22]. However, even for now controversies and blind spots still remain in the observation of basic flame dynamics and its interpretation. Various mechanisms of tulip flame formation have been proposed, e.g. quenching and viscous effect, flame-induced flow, pressure wave effect, Darrieus–Landau instability, vortex motion in the burnt gas and Taylor instability [18,23–26]. Markstein [27] observed analogous flame indentation to tulip shape by laminar flame and shock wave interactions, and explained it by modified Taylor instability theory. But Starke et al. [28] and Clanet et al. [29] believed that the Taylor instability was driven by the deceleration of flame tip while neither shock wave nor pressure wave was necessary. And it was wall-quenching effect that reduced the flame area leading the

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subsequent deceleration. Through numerical simulation, Dunn-Rankin et al. [23] and Gonzalez et al. [30] suggested, the transversal velocity gradient along the flattened front (i.e. squish flow) and Darrieus-Landau instability played crucial roles in tulip inversion. Furthermore, Gonzalez et al. [30] also found the deceleration in the central part (i.e. flame tip) was important. Nevertheless, the mathematical analyses by Matalon and Metzener [26] supported the vortex motion in the burned gas leading to the tulip formation. Generally, none of these mechanisms has rigorously accounted for tulip flame phenomenon. Accordingly, Dunn-Rankin [24] proposed that, the tulip flame could be resulted from a combined effect of different mechanisms.

Decades after Ellis first captured the tulip flame, Clanet and Searby [29] first divided the flame dynamics and shape changes of premixed flame in half-open and closed tubes into four stages: (1) hemispherical expansion flame unaffected by side walls; (2) finger-shaped flame with exponential growth rate; (3) elongated flame with skirt touching the side walls; (4) classic tulip inversion. Recently Xiao et al. [31] revealed a remarkable “distorted tulip” phenomenon of premixed hydrogen–air flame in a closed tube with hydrogen concentration ranging from 26% to 64% (by volume in air). After the classic tulip inversion, the flame would be further distorted with primary tulip lips dented to the wall forming growing secondary cusps (i.e. triple tulip). Xiao et al. [32] concluded that, the pressure wave triggered by the contact of the flame with the duct sidewalls played a dominant role in the formation of the distorted tulip flame. And the process was the same as that in the flame-shock wave interaction experiments of Markstein. Nevertheless, few studies were reported to explore this phenomenon in simple hydrocarbon gases. Probably the distorted tulip is intrinsic and universal for premixed flame in closed ducts, but more prominent for highly reactive hydrogen. A more comprehensive view of distorted tulip flame formation and the role played by pressure wave during the flame propagation is fairly beneficial for the understanding of the mechanism.

Although there have been a number of studies on premixed flame propagation in closed ducts, the additional information regarding the determinant conditions that lead to tulip flame and tulip distortion is still required. The flame behaviors should be observed in a wider equivalence ratio range for full consideration. The quantitative analyses of experimental observations are still insufficient for numerical and analytical modeling. Bychkov et al. developed an analytical theory of flame propagation in a long half-open cylindrical tube for characterizing the acceleration process. However, the theory worked well just in a narrow range of equivalence ratios at very early stages for premixed propane–air flames [18].

In this work, experiments were performed for both premixed hydrogen–air and premixed propane–air flames in a closed duct. High-speed schlieren images and pressure dynamics were recorded for detailed analyses and comparison. The common phenomena of different flames were explored. The underlying mechanisms of distorted tulip flame formation, especially the pressure wave effect, were discussed. This work can provide more knowledge of flame dynamics in ducts for numerical and theoretical modeling, deflagration to detonation transition, and safety design in industry.

2. Experimental method

The experimental set-up mainly consists of a constant volume combustion chamber (82 mm × 82 mm × 530 mm), a high-speed video camera, a schlieren system, a pressure recording system, a gas mixing device and a synchronization controller and a high-voltage ignition system, as shown in Fig. 1. Complete details of the experimental system and procedure have been also described elsewhere [33].

The combustion chamber is a horizontal rectangular duct with strictly parallel side walls made of optically excellent quartz glass for viewing the flame behaviors through high-speed schlieren photography. The top and bottom walls are TP304 stainless steel instead. Before experiments, the combustion chamber would be closed through sealing the pressure relief opening by a diaphragm with certain thickness. The diaphragm would break up near the end of the combustion for safety sake once its overpressure threshold is achieved.

The mixture is ignited by a pair of spark electrodes (with 2 mm gap on the duct axis) 5.5 cm away from the left end wall. The subsequent flame propagation is captured graphically 15,000 frame/s by a high-speed video camera (Photron, Fastcam Ultima APX, Max 120,000 fps) combining schlieren system. For collecting more details of the pressure field in the duct, the pressure changes are measured by three evenly-spaced pressure sensors PCB 112B10 along the top wall. The synchronization controller triggers the ignition and the recording devices simultaneously for better data acquisition.

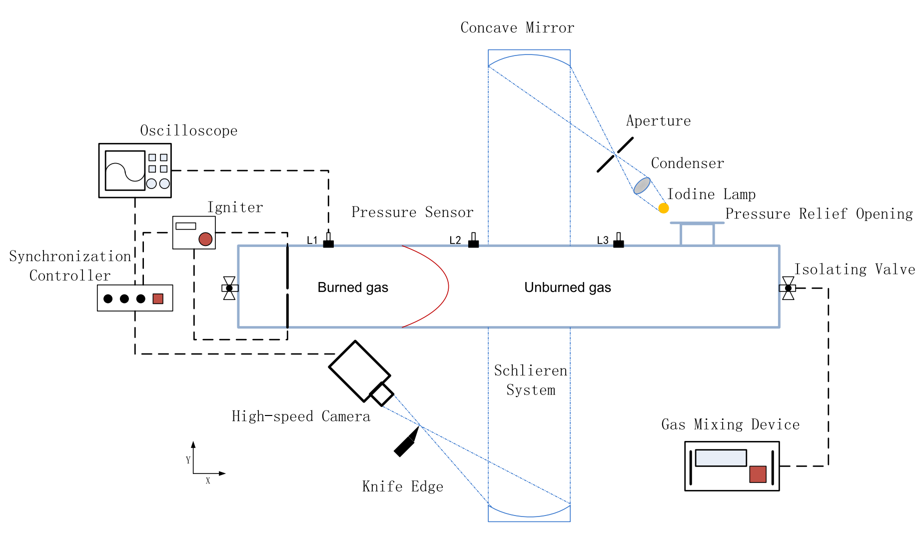

Fig. 1. Schematic diagram of the experimental apparatus.