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An experimental study of premixed hydrogen/air flame propagation in a partially open duct

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ABSTRACT

High-speed schlieren cinematography and pressure records are used to investigate the dynamics of premixed hydrogen/air flame propagation and pressure build up in a partially open duct with an opening located in the upper wall near the right end of the duct. This work provides basic understanding of flame behaviors and the effects of opening ratio on the combustion dynamics. The flame behaves differently under different opening conditions. The opening ratio has an important influence on the flame propagation and pressure dynamics. When the opening ratio $\alpha \leq 0.075$ a significant distorted tulip flame can be formed after the full formation of a classical tulip flame. The propagation speed of flame leading tip increases with the opening ratio. The coupling of flame front with the pressure wave is strong at low opening ratio. Both the pressure growth rate and oscillation amplitude inside the duct increases as the opening ratio decreases. The formation times of tulip and distorted tulip flames and the corresponding distances of flame front increase with the increase of the opening ratio.

1. Introduction

Flammable gas explosion hazards in confined region remain a significant concern in process industries [1–5]. Premixed flame dynamics in tubes is of great importance since it represents the early acceleration stage in deflagration to detonation transition (DDT) and models the burning process in internal combustion engines [1–3,6–10]. The hydrogen safety involving fire and explosion is one of the key issues at the forefront associated with the forthcoming hydrogen economy, and the premixed hydrogen combustion dynamics is thus important for the hydrogen safety engineering [1,3,11–17].

Generally, premixed flame in tubes undergoes a variety of shape changes [1,9,18–21], such as curved, tulip, distorted tulip and cellular fronts, due to hydrodynamic and combustion instabilities. Flame acceleration in obstructed channels is usually fairly strong and could result in DDT [2,5,22]. Weak ignition at/near the center of the end wall of a smooth tube commonly leads to a semi-spherical/spherical laminar flame, which evolves into a finger shape front later on [7,8,10,21,23]. The finger flame experiences short but powerful acceleration till the flame skirt reaches the sidewalls of the tube. Then the flame acceleration stops, and the flame skirt catches up with the flame tip rapidly. Under specific geometrical conditions (e.g. aspect ratio larger than two in a closed tube), the flame can invert into a tulip shape [7–9,21,24]. In particular, premixed hydrogen/air flame can further deform into a distorted tulip shape after the full formation of a classical tulip flame [20,21]. The distorted tulip flame develops into a salient "triple tulip" shape as the secondary tulip cusps approach the center of the primary tulip tongues. The dynamics of a distorted tulip flame

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has been demonstrated to be different from that of a classical tulip flame.

A large number of experimental, analytical and numerical studies have been devoted to the tulip phenomena and its formation mechanism [7–10,18,23–30]. Various possible explanations have been put forward: quenching and viscosity effects [10,27], interaction between flame and pressure wave [31], Darrieus-Landau (DL) instability [25,32], flame–vortex interaction [9,24] and Taylor instability [8]. In fact, the tulip formation may not be determined by a single mechanism since it is sensitive to numerous factors. Dunn-Rankin and Sawyer [23] carried out an experimental parametric study of tulip flame formation and concluded that the geometry of combustion vessel and mixture composition are important for the tulip formation. Clanet and Searby [8] performed an experimental and analytical study of premixed flame propagation in half-open tube and suggested four stages for the tulip flame propagation, namely spherical flame, finger-shaped flame, flame with its skirt touching sidewalls and tulip flame. They also proposed that the only relevant parameters are the laminar burning velocity, diameter of the tube and thermal gas expansion ratio. Based on the four stages of flame dynamics, Bychkov et al. [7] developed an analytical theory of the finger shape flame acceleration and tulip formation in long half-open tubes and found that the tulip formation does not depend on the Reynolds number. This theory was successfully validated against the experiment by Clanet and Searby [8] as well as DNS simulations. The experimental and LES investigation by Xiao et al. [21] shows that the pressure wave triggered by the first contact of the flame with the sidewalls of the duct plays an important role in the dynamics and formation of a distorted tulip flame. On the basis of LES simulation of the same experiment, Xiao et al. [21] thought that vortex motion generated in the burnt gas by the interaction between flame front, flow and pressure wave creates the conditions required for the formation of a distorted tulip flame. Additionally, a detailed investigation of influence of equivalence ratio on flame dynamics with tulip and distorted tulip shapes for hydrogen/air mixture both in half-open and closed ducts is given in [20].

The present work describes an experimental study of premixed hydrogen/air flame propagation in a partially open duct. The primary objective of this investigation is to provide an understanding of the premixed hydrogen/air flame behavior in a partially open duct, and to examine the effects of opening condition on the flame propagation. First, experiments on premixed hydrogen/air flames propagating from the closed end to the open one is presented to reveal the flame characteristics in a partially open duct at different opening conditions. And then, the effects of the opening ratio on the flame behavior are scrutinized in detail.

2. Experimental apparatus

The experimental apparatus is schematically shown in Fig. 1. It consists of a gas mixing system, a high-speed schlieren photometry system, a pressure transducer, a high-voltage ignition system, a constant volume combustion duct and a synchronization controller. The combustion chamber, which is located horizontally in the center of the optical path of the schelieren system, is a partially-open duct 82 mm square by 530 mm long. A circular opening (vent orifice) is set up in the upper wall near the right end of the duct. The center of the opening is located on the longitudinal centerline at a distance of 7.5 cm from the right end face of the duct. The two side panels of the combustion duct are constructed of quartz glass to allow optical access. The upper and lower walls are made of TP304 stainless steel. In order to examine the influence of opening condition on the flame propagation, an opening ratio α is defined here as the ratio of open area to the area of the duct cross-section (open area/area of the duct cross-section). The high-speed schlieren system is adopted to capture the variations in the flame shape and position with time. The schlieren system arranged in a standard Z-configuration is composed of a point light source (iodine lamp with a 2.0 mm aperture), a high-speed video camera, a vertical knife edge, two focusing lenses, and two spherical concave mirrors (2.0 m focal length). During the flame propagation the pressure inside the duct is recorded using a PCB Piezotronics model 112B10 quartz transducer located at the bottom of the duct 7.5 cm from the right end wall.

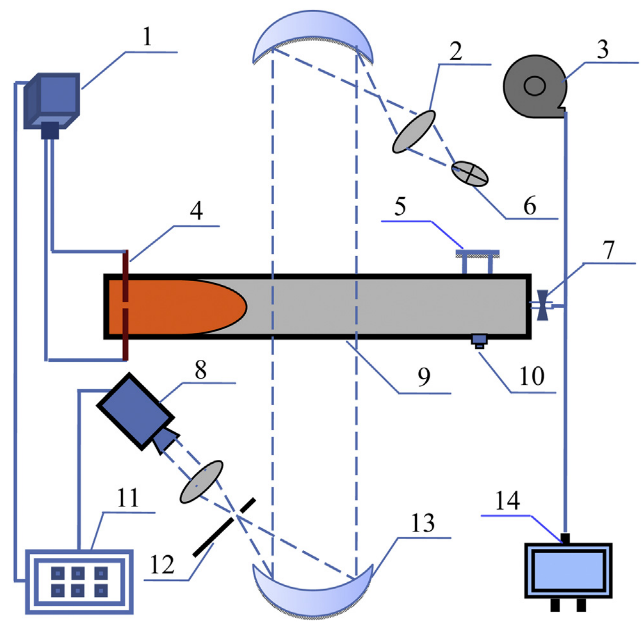

Fig. 1 – Sketch of experimental set-up: (1) spark igniter, (2) focusing lens, (3) vacuum pump, (4) ignition electrode, (5) vent orifice (opening), (6) point light source, (7) isolation valve, (8) high-speed video camera, (9) combustion duct, (10) pressure transducer, (11) synchronization controller, (12) schlieren knife edge, (13) schlieren mirror, (14), gas mixing device.

The vessel is evacuated using a vacuum pump before gas filling. The duct is filled with a premixed mixture of hydrogen and dry air with hydrogen concentration 30% in volume. The mixture is fed into the right end wall of the duct through an isolating valve. The initial temperature and pressure in the experiment are $T_0 = 298$ K and $P_0 = 101325$ Pa, respectively. A short time delay of approximately 30 s is incorporated into the filling sequence before ignition to allow the mixture to