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Experimental study on a comparison of typical premixed combustible gas-air flame propagation in a horizontal rectangular closed duct

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HIGHLIGHTS

- Natural gas, methane, and acetylene present quite different flame dynamics due to their different compositions.
- Tulip flame forms with equivalence ratio $0.72 \leq \Phi \leq 1.44$ for natural gas, $0.79 \leq \Phi \leq 1.30$ for methane, $0.40 \leq \Phi \leq 1.70$ for acetylene.
- Small amount of ethane etc. existing in natural gas provide it a wider equivalence ratio range in tulip flame formation.
- Acetylene has the fastest flame tip speed and the maximal pressure, while methane shows the slowest and minimal one.
- The Bychkov theory coincides well with the experimental data in the case of equivalence ratios close to 1.00.

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ABSTRACT

Research surrounding premixed flame propagation in ducts has a history of more than one hundred years. Most previous studies focus on the tulip flame formation and flame acceleration in pure gas fuel-air flame. However, the premixed natural gas-air flame may show different behaviors and pressure dynamics due to its unique composition. Natural gas, methane and acetylene are chosen here to conduct a comparison study on different flame behaviors and pressure dynamics, and to explore the influence of different compositions on premixed flame dynamics. The characteristics of flame front and pressure dynamics are recorded using high-speed schlieren photography and a pressure transducer, respectively. The results indicate that the compositions of the gas mixture greatly influence flame behaviors and pressure. Acetylene has the fastest flame tip speed and the highest pressure, while natural gas has a faster flame tip speed and higher pressure than methane. The Bychkov theory for predicting the flame skirt motion is verified, and the results indicate that the experimental data coincide well with theory in the case of equivalence ratios close to 1.00. Moreover, the Bychkov theory is able to predict flame skirt motion for acetylene, even outside of the best suitable expansion ratio range of $6 < E < 8$.

1. Introduction

Gaining an understanding of dynamics of premixed flame propagation in confined spaces is of great importance in terms of explaining both gas explosion dynamics and the burning processes of typical internal combustion engines [1]. It represents the initial flame acceleration stage and the development of detonation waves [2]. Combustible gas fuel have become widely applied in industry and in daily life over decades. However, serious explosion accidents occur almost annually worldwide due to the difficulties faced in controlling gases and their dangerous characteristics. It is thus desirable for studies to be undertaken into the premixed combustion behavior of typical fuel-air gas both in terms of safety and the engineering applications of combustion [3,4].

Research into premixed flame propagation in ducts has a history spanning more than one hundred years. Ellis first reported the inversion images of premixed flame surfaces in 1928, subsequent to which this special flame shape was named the "tulip" flame by Salamandra [5]. A large volume of literatures have been reported upon the formation process and mechanism of the "tulip" flame, but the formation mechanism of this particular flame has failed to be reported conclusively so far. Dunn-Rankin and Sawyer [6] declared the "tulip" flame to be composed of a series of flame propagation

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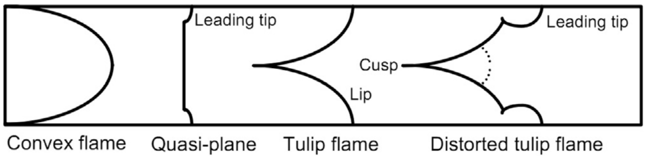

Fig. 1. Geometrical sketch of distorted tulip flame.

process combinations based on a large number of experimental studies. The propagation process of the "tulip" flame is divided into four kinetics stages, according to the experimental study conducted by Clanet and Searby [7]. Empirical models are established for each stage, and the formation time of each stage and flame front location can be calculated. Bychkov et al. [1] put forward the theoretical model of the "tulip" formation and flame acceleration in its early stages and suggested that the formation of the "tulip" flame is unrelated to the Reynolds number of the flame. Gonzalez [8] studied the interaction between the flame and the acoustic wave in a closed duct using a numerical simulation method. He proposed that the flame shape changes in the later stage and the periodic oscillation phenomenon were the result of interactions between the flame front and the pressure wave, and that the mechanism could be explained by Taylor instability. Markstein [9] studied the interaction between the shock wave and the laminar premixed flame by schlieren experimental technology. The inversion appeared in the flame front when it met with shock waves, and the flame formed a shape similar to the "tulip" at the same time. He argued that the direct reason for flame front inversion is the sudden deceleration of the flame caused by the shock wave, and the inner mechanism was explained by Taylor instability.

A variety of alternative possible explanations for the tulip flame have been proposed: quenching and viscosity effects, interaction between flame and pressure wave, Darrieus-Landau instability, large circulation in the burnt gas and so on. Xiao et al. [10] suggested that flame propagation is strongly influenced by the initial and boundary conditions, such as initial temperature and pressure, heat loss and wall effects. The mixture composition and aspect ratio of tubes are also important. An interesting phenomenon of the "distorted tulip flame" has been reported [11,12]. It has been found that the distorted tulip flame is initiated near the tips of tulip lips and deforms into a salient "triple tulip" shape as the secondary tulip cusp approaches the center of the primary tulip lips [12], as shown in Fig. 1. Xiao et al. [11] defined it as the fifth stage of the premixed flame based on the four stages theory proposed by Clanet and Searby [7]. It has been put into evidence that the dynamics of the distorted tulip flame is different from those of the classical tulip flame [12].

Although a large number of studies have been conducted into premixed flame propagation in ducts, most focus on tulip flame formation and flame acceleration in pure gas fuel-air flames. Premixed natural gas may exhibit different flame behaviors and pressure dynamics due to its unique compositions in comparison with pure methane. Moreover, acetylene, with its very high chemical reactivity, is also chosen to make a comparison with methane and natural gas. This paper aims to study the different flame behaviors and pressure dynamics of natural gas, methane, and acetylene, and to explore the influence of the composition of the gas mixture on premixed flame dynamics.

2. Experimental apparatus and procedures

The experimental apparatus is schematically shown in Fig. 2. It consists of a constant volume rectangular combustion duct, a high-speed schlieren photography system, a pressure recording system, a gas mixing system, a high-voltage ignition system, and a synchronization controller. The combustion duct, which is located in the center of the optical path of the schlieren system, is a horizontal straight rectangular duct with the inner size of 82 mm × 82 mm × 530 mm. In order to observe flame behavior and shape changes during propagation, the two side panels of the duct are made of quartz glass with a thickness of 1.6 cm to provide optical access. Meanwhile, the upper and lower walls are made of TP304 stainless steel with the thickness of 1.5 cm. The schlieren system, which is placed in a standard *Z*-configuration, consists of a point light source (an iodine lamp with a 2.0 mm aperture), a vertical schlieren knife edge, two focusing lenses, two spherical concave mirrors (2.0 m focal length), and a high-speed video camera. A discharge vent, with a diameter of 4.0 cm, and which is initially closed, is set up in the upper wall 7.5 cm to the right end face of the duct for safety.

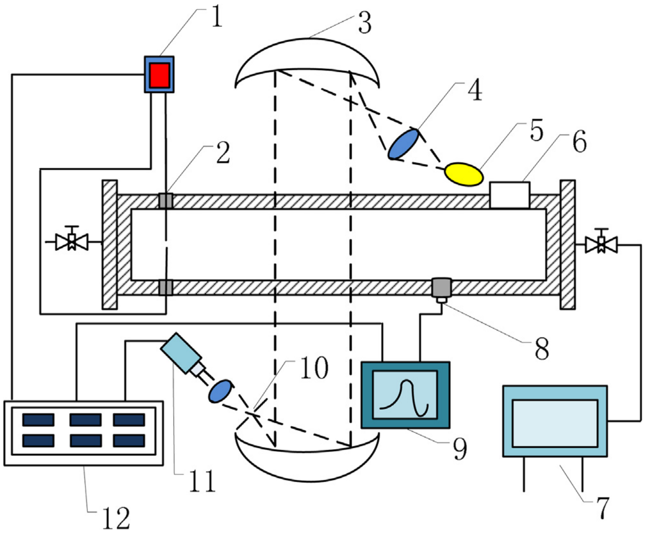

Fig. 2. Sketch of premixed flame propagation experimental apparatus: (1) spark igniter, (2) ignition electrode, (3) schlieren mirror, (4) focusing lens, (5) point light source, (6) discharge vent, (7) gas mixing device, (8) pressure transducer, (9) data recorder, (10) knife edge, (11) high-speed video camera, and (12) synchronization controller.

Experiments are conducted with premixed natural gas-air, methane-air, and acetylene-air mixture at different equivalence ratios. The equivalence ratio Φ is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. It should be noted that the natural gas used in this study is provided by a gas company in Hefei, and it is composed of CH_4, C_2H_6, N_2, CO_2, and C_3H_8, in addition to other hydrocarbons, with concentrations of 95.38%, 2.24%, 1.10%, 0.67%, 0.39%, and 0.22%, respectively. The combustible mixture is prepared by the partial pressure method using a gas mixing system. The initial pressure and temperature are 101325 Pa and 298.15 K, respectively. The mixture is ignited by a single spark which is located on the symmetry axis at a distance of 5.5 cm to the left end face of the duct. A short time delay of about 30 s is incorporated into the filling procedure before ignition to ensure the mixture becomes essentially quiescent. High-speed schlieren photography is adopted to provide visible images of the flame shape changes and determine the flame tip speed. The operating speed of the high-speed video camera (FASTCAM Ultima APX) is 15000 frame/s. A time history of the pressure in the duct is obtained using a transducer (PCB Piezotronics model 112B10) located at the central line of the bottom face of the duct, 130 mm to the right end. The spark igniter, high-speed video camera, and data recorder are triggered simultaneously using a synchronization controller system. Repeat experiments (three) are carried out, the results of which