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Dynamics of premixed hydrogen/air flame in a closed combustion vessel

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ABSTRACT

The dynamics of a premixed hydrogen/air flame propagating in a closed vessel is investigated using high-speed schlieren cinematography, pressure measurement and numerical simulation. A dynamically thickened flame approach with a 19-step detailed chemistry is employed in the numerical simulation to model the premixed combustion. The schlieren photographs show that a remarkable distorted tulip flame is initiated after a classical tulip flame has been fully produced. A second distorted tulip flame is generated with a cascade of indentations created in succession before the vanishing of the first one. The flame dynamics observed in the experiments is well reproduced in the numerical simulation. The burnt region near the flame front is entirely dominated by a reverse flow during the formation of the distorted tulip flame. The distorted tulip flame can be formed in the absence of vortex motion. The pressure wave leads to periodic flame deceleration and plays an essential role in the distorted tulip formation. The numerical results corroborate the mechanism that the distorted tulip flame formation is a manifestation of Taylor instability.

1. Introduction

The current energy demand all over the world is primarily based on fossil fuels. However, the reserves of fossil fuels become increasingly exhaustible [1]. In addition, great interest in new alternative fuels is generated by the economic and environmental concerns associated with the utilization of fossil fuels, i.e. high fuel price, global warming and atmosphere pollution [1,2]. Hydrogen as energy carrier is one of the most promising options and merits long-term development [1,2]. It can be used to generate energy via various methods, e.g. fuel cell, internal combustion engine and gas turbine. Nevertheless, there are also serious challenges when using hydrogen as an energy carrier. The major combustion-related problems are the unique characteristics of hydrogen due to its high reactivity and diffusivity, which can lead to pre-ignition, flashbacks, and explosions [1–4]. As a result, hydrogen combustion research is a key issue at the forefront. Dynamics of premixed combustion in tubes is of great importance because it models the typical burning process in internal combustion engines and the early stage in the development of detonation waves [2,5–10].

Generally, a flame propagating in a tube can experience various shape changes, e.g. spherical, curved, tulip, and cellular fronts [1,5,6,11]. Mild ignition usually initiates a slow laminar flame, which can be wrinkled later on by a variety of instabilities. The premixed flame dynamics is sensitive to different mechanisms, such as hydrodynamic instability,

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thermal-diffusion instability, acoustic wave (pressure wave) and vortex flow [2,6,7,11,12]. In particular, a tulip flame can be created in a closed tube when the aspect ratio is larger than two [13]. Numerous experimental, analytical and numerical studies have been carried out aiming to explain the tulip flame formation [5,6,14–21]. Various possible mechanisms have been proposed: effects of viscosity and quenching [13,22], interaction between flame front and pressure wave [23], Darrieus–Landau (DL)/hydrodynamic instability [17,19,20], circulating flow in the burnt gas [6,12,24] and Taylor instability [15]. Bychkov et al. [14] developed an analytical theory of tulip flame propagation in long half-open tubes and found that the tulip formation is independent of the Reynolds number. The interaction between the flame front and the near-field flow plays an important role in the flame stability [25] and tulip flame formation [6,16]. The initiation of flame deformation could be in relation to the DL instability [19], but the tulip flame formation cannot be explained by this instability [6,12]. It has been also put into evidence that the pressure wave is of lesser importance for the tulip flame formation [15]. Nevertheless, the numerical study by Gonzalez [11] shows that the flame dynamics at the later stage in a closed duct has a close connection with the acoustic waves. Moreover, the shock tube study by Markstein [26] shows that a flame indentation which is pretty similar to the tulip shape is produced due to the flame–shock interaction.

Premixed hydrocarbon/air flames in closed vessels generally exhibit characteristic features of classical tulip flame. The flame dynamics of hydrogen in air could be different from that of hydrocarbon fuels due to its unique properties, e.g. higher laminar burning velocity, larger diffusivity and greater extinction strain rates than hydrocarbon fuels. Recent works have revealed a curious phenomenon of premixed flame for hydrogen/air mixture in a closed tube, i.e. the "distorted tulip" flame [27,28]. It was experimentally shown that a distorted tulip flame is produced when hydrogen concentration ranges from 26% to 64% by volume in air after a classical tulip flame has completely formed. The distortions (secondary tulip cusps) are initially generated near the tips of the primary tulip lips. The distorted tulip flame forms into a salient "triple tulip" shape as the secondary cusps approximately arrive at the center of the lips of the primary tulip flame. Furthermore, a second distorted tulip flame can be created before the collapse of the first one [29]. It has been demonstrated that the dynamics of a distorted tulip flame differs from that of a classical tulip flame [27,28]. Xiao et al. [28] suggested that the interaction among the flame front, pressure wave and the combustion-generated flow assumes a dominant role in the formation of distorted tulip flame [28]. Based on numerical simulations, they qualitatively concluded that the distorted tulip flame is generated due to the vortex motion behind the tulip front. However, the vortices in the vicinity of flame front may be produced by a curved flame shape [2]. It implies that the vortical motion may not be necessarily the determining factor for the creation of the distorted tulip formation. In the most recent experimental study [29], another mechanism, i.e. the Taylor instability, was proposed.

This work presents an experimental and numerical investigation of premixed flame dynamics in a closed vessel. The present study aims to further understand the mechanism of premixed flame propagation for hydrogen/air mixture. Experiments are conducted to characterize the dynamics of the premixed flame firstly. And then, numerical simulation based on a dynamically thickened flame (TF) model is performed to gain an insight into the physical process of the flame evolution. Note that a part of the experimental data (i.e. the schlieren images of the later flame stage, propagation speed of flame tip and pressure growth rate) was briefly invoked to characterize the distorted tulip flame in the earlier experimental work [29].

2. Experimental methods

The details of the experimental setup and methodology were given in the earlier reports [27,28] and thus only a succinct outline is repeated here. The evolution of flame shape and position with time during the combustion process are recorded using a high-speed schlieren system. The schlieren system is arranged in a standard Z configuration. The high-speed video camera is operated at a speed of 15,000 frame/s. The pressure build-up inside the chamber is recorded by a PCB Piezotronics quartz transducer (model 112B10). The transducer is located at the longitudinal centerline of the duct bottom 7.5 cm from the right endwall.

The combustion chamber is a closed duct 8.2 cm square by 53 cm long. The two side windows of the vessel are constructed of quartz glass to provide optical viewing. It is important to use parallel sidewalls for schlieren photography and there is little qualitative difference between tulip flame propagation in square cross-section and circular cross-section tubes [30]. The combustion vessel, which has been evacuated using a vacuum pump before gas filling, is filled with a hydrogen/air mixture with hydrogen concentration 30% by volume. The initial temperature (T_0) and pressure (p_0) inside the chamber are approximately 298 K and 101,325 Pa, respectively. The flammable mixture is allowed to be quiescent before ignition. The ignition site is a single spark gap (approximately 1 mm) located on the duct axis 5.5 cm from the left endwall.

3. Numerical model

Though large eddy simulation was applied in the earlier work, the flow during the distorted tulip flame propagation in a closed duct turns out to be substantially laminar [28]. It has been demonstrated that the premixed flame propagation in a closed duct can be successfully simulated using a two-dimensional numerical approach, and the predicted tulip flame and subsequent deformations are quite compatible with those observed in experiment [16,18,22]. The transient flame propagation for the premixed hydrogen/air mixture is simulated as a two-dimensional laminar reacting flow in this study. The governing equations, which are composed of conservation equations for mass, momentum, energy, and species, are given below:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j}, \tag{2}$$