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Experimental and numerical study of premixed hydrogen/air flame propagating in a combustion chamber

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HIGHLIGHTS

- A tulip flame is repeated after the collapse of the distorted tulip flame.
- The effect of wall friction on premixed hydrogen/air flame propagation is studied.
- Tulip and distorted tulip flames can be formed in the absence of wall friction.
- The distorted tulip flame can be created without the effect of vortex motion.
- The TF model with detailed chemistry is reliable for studying hydrogen explosion.

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ABSTRACT

An experimental and numerical study of dynamics of premixed hydrogen/air flame in a closed explosion vessel is described. High-speed shlieren cinematography and pressure recording are used to elucidate the dynamics of the combustion process in the experiment. A dynamically thickened flame model associated with a detailed reaction mechanism is employed in the numerical simulation to examine the flame-flow interaction and effect of wall friction on the flame dynamics. The shlieren photographs show that the flame develops into a distorted tulip shape after a well-pronounced classical tulip front has been formed. The experimental results reveal that the distorted tulip flame disappears with the primary tulip cusp and the distortions merging into each other, and then a classical tulip is repeated. The combustion dynamics is reasonably reproduced in the numerical simulations, including the variations in flame shape and position, pressure build-up and periodically oscillating behavior. It is found that both the tulip and distorted tulip flames can be created in the simulation with free-slip boundary condition at the walls of the vessel and behave in a manner quite close to that in the experiments. This means that the wall friction could be unimportant for the tulip and distorted tulip formation although the boundary layer formed along the sidewalls has an influence to a certain extent on the flame behavior near the sidewalls. The distorted tulip flame is also observed to be produced in the absence of vortex flow in the numerical simulations. The TF model with a detailed chemical scheme is reliable for investigating the dynamics of distorted tulip flame propagation and its underlying mechanism.

1. Introduction

The reserves of common fossil fuels are now exhaustible [1]. Great interest in new alternative fuels is generated by the economic and environmental concerns in the use of fossil fuels, i.e. high fuel price, global warming and environmental pollution. Hydrogen is one of the promising alternative fuels in the future because of its potentially high efficiency and ultra-low harmful emissions [1,2]. However, there are serious challenges to overcome when using hydrogen as an energy carrier. The major problems in relation to combustion are the unique characteristics of hydrogen due to its high diffusivity and reactivity, which can lead to flashbacks, pre-ignition and explosion hazards [1–3]. Flame dynamics in combustion vessels is one of the important subjects of fundamental study since it has a close relation to the development of a detonation wave in explosions and can characterize the burning process in a typical internal-combustion engine as well as other industrial configurations [1,4–12].

Basically, a premixed flame propagating in a tube is intrinsically unstable and can exhibit a series of shape changes, such as curved, tulip and distorted tulip fronts [4,5,13–16]. Weak ignition of combustible mixture generally leads to a slow laminar flame. The expansion of hot combustion products pushes a flow in the

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unburned mixture and results in spontaneous flame acceleration later on under confinement in a tube. The combustion-generated flow interacts with the flame front and influences the flame dynamics in turn. The fluid flow is complicated and time-dependant during the transient flame propagation. The initially smooth flame front can be wrinkled by the intrinsic Darrieus–Landau (DL) and combustion instabilities. The wrinkling effect generates additional increase in flame surface area and further the flame acceleration. Earlier experiments of premixed flames in closed tubes by Ellis [17] revealed a quite interesting phenomenon, i.e. the tulip flame, which is characterized by a cusp pointing toward the burnt region. The tulip flame can also be produced in a half-open tube and behaves in the same way [18]. A large number of works have been conducted to investigate the dynamics of the tulip flame and explain its formation mechanism. Various explanations have been given: effects of viscosity and quenching [17,19], Taylor instability [18], interaction between flame and acoustic wave (pressure wave) [20], vortical flow behind the flame front [7,21] and DL instability [22,23]. Clanet and Searby [18] carried out an experimental and analytical study of the tulip flame formation and thought that both the pressure wave and the boundary layer are of minor importance for the tulip formation. Nevertheless, Marra and Continillo [19] performed a numerical simulation using a full Navier–Stokes method and argued that the viscous flow near the tube sidewalls is important for the flame dynamics and the wall friction plays a crucial role in the onset of tulip flame. Based on experimental measurement and numerical simulation, Dunn-Rankin et al. [24] suggested that the tulip flame can be caused by the hydrodynamics of flame-induced flow. The flame inversion may be related to the DL instability, but the tulip flame could not be explained by this instability [21]. The vortex motion near the flame front is usually created in the burnt gas after the fame has touched the sidewalls and can invert the flame into tulip shape [21]. More recently, Bychkov et al. [4] developed an theoretical model of the early flame acceleration and tulip flame propagation in half-open tubes and concluded that the formation of tulip flame can be independent of the Reynolds number.

Another important flame phenomenon recently reported for premixed hydrogen/air mixture is the "distorted tulip" flame [15,25]. It was observed in the experiments that a significantly distorted tulip flame can be formed in a closed duct in the hydrogen concentration range of 26–64% by volume. The distortions are created initially from the tips of the primary tulip tongues after a well-pronounced classical tulip flame has been formed. It has been demonstrated that the dynamics of a distorted tulip flame differs from that of the classical tulip flame remarked above. The pressure wave plays an essential role in the dynamics of distorted tulip flame, and the distorted tulip formation could have a connection with the circulating flow in the burnt gas or Taylor instability driven by the drastic flame deceleration [15,26]. Although the distorted tulip flame exhibits more complex characteristics than the classical tulip flame, the dynamics and mechanism of distorted tulip flame have not been well understood. For example, the mechanism of Taylor instability is not supported by an analytical theory, and there is a lack of a theoretical model to predict the evolution of distorted tulip flame. The conditions for the appearance of a distorted tulip flame is not sufficiently clear either, e.g. the effects of wall friction, viscosity and vortex motion. Besides, it could be also interesting to examine the development of a distorted tulip flame in a hydrogen/air mixture at a low/high equivalence ratio (with smaller laminar flame speed and expansion ratio) since the distorted tulip flame was only investigated in detail for near-stoichiometric hydrogen/air mixtures in [15,26].

The scope of the present work is to experimentally and numerically investigate the dynamics of premixed flame propagation and the effect of wall friction on flame in a closed combustion vessel. First, experiments are carried out to examine the flame dynamics with tulip and distorted tulip shapes for a hydrogen/air mixture at a high equivalence ratio. Then numerical simulations using a dynamically thickened flame approach are conducted to elucidate the influence of wall friction on the premixed flame dynamics. The interaction of the flame front with its self-generated flow is also studied to gain an insight into the formation of tulip and distorted tulip flames under different boundary conditions at the walls of the chamber.

2. Experimental setup

The experimental setup is mainly composed of a constant volume combustion chamber, a gas mixing system, a high-voltage ignition system, a pressure detecting system, and a high-speed schlieren cinematographic system. The experimental apparatus and methodologies were described in detail in the previous studies [15,25] and only a brief outline is given here. The explosion chamber is a horizontal closed rectangular duct 8.2 cm square by 53 cm long. The two lateral panels of the duct are constructed of quartz glass for allowing optical access. The time evolution of flame structure and location during the burning process are captured using the high-speed schlieren system. The high-speed cinematograph camera is operated at a rate of 15,000 frame/s. A PCB Piezotronics quartz transducer (model 112B10) is used to record the pressure transient in the chamber. The transducer is placed at the longitudinal centerline of the bottom of the duct, 7.5 cm from the right end wall. The flammable gas is a hydrogen/air mixture with equivalence ratio $\Phi = 3.57$. The experiments are conducted at the initial temperature $T_0 \approx 298$ K and pressure $p_0 \approx 101{,}325$ Pa, respectively. The combustible mixture is allowed to become quiescent by incorporating a short time delay (approximately 30 s) into the gas filling sequence before ignition. The ignition source is a single spark gap located on the axis at a distance of 5.5 cm from the left endwall of the vessel.

3. Numerical methods

3.1. Governing equations

Computational fluid dynamics is widely applied in the research of energy and combustion science [2,27,28]. The fluid flow in the transient flame development with tulip and distorted tulip shapes in a laboratory scale closed tube has been demonstrated to be substantially laminar [4,15]. And the premixed flame dynamics can be correctly modeled by a two-dimensional (2D) laminar approach [19,24,29]. The propagating premixed flame is simulated as a 2D laminar reacting gas flow in the present work. The governing equations consisting of conservation equations of mass, momentum, energy and species are as follows:

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

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

$$\sigma_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij}, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial x_i}(u_i(\rho e + p)) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i} - \sum h_m J_m + u_j\sigma_{ij}\right) + \dot{Q}_c, \tag{4}$$