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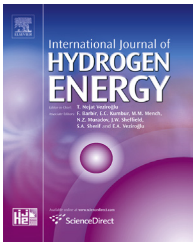

Effects of ignition location on premixed hydrogen/air flame propagation in a closed combustion tube

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ABSTRACT

The dynamics of premixed hydrogen/air flame ignited at different locations in a finite-size closed tube is experimentally studied. The flame behaves differently in the experiments with different ignition positions. The ignition location exhibits an important impact on the flame behavior. When the flame is ignited at one of the tube ends, the heat losses to the end wall reduce the effective thermal expansion and moderate the flame propagation and acceleration. When the ignition source is at a short distance off one of the ends, the tulip flame dynamics closely agrees with that in the theory. And both the tulip and distorted tulip flames are more pronounced than those in the case with the ignition source placed at one of the ends. Besides, the flame–pressure wave coupling is quite strong and a second distorted tulip flame is generated. When the ignition source is in the tube center, the flame propagates in a much gentler way and the tulip flame can not be formed. The flame oscillations are weaker since the flame–pressure wave interaction is weaker.

Introduction

Flame dynamics in tubes is one of the important subjects of combustion research [1–11]. The premixed flame propagation in a hydrogen/air mixture is of particular interest in the application of safety and operation of internal combustion engines [12–16]. The flame in a tube is more complex than a freely propagating flame. The thermal expansion of the combustion products plays a key role in the early flame acceleration [2,4]. The flame behavior can be influenced by different parameters such as boundary layer, acoustic waves and heat losses at the walls. And the flame is unstable due to the intrinsic hydrodynamic instability that results from thermal expansion. Various observations on premixed flame in closed and half-open tubes were reported. One of the curious phenomena is the tulip flame which is characterized by a shape concaved from the unburned mixture to the burnt gas [4,17–19]. The visual results of premixed flame propagation in closed tubes were first reported by Ellis [20]. In his experiments, a curved flame convex toward the unburned gas suddenly flattens and turns concave toward the burnt gas subsequent to a rapid deceleration. Generally, the flame maintains this tulip shape through the rest of the propagation. The tulip flame can be also formed in half-open tubes [4].

Many studies have been focused on the tulip flame phenomenon because of its complexity [2,4,7,10,11,18,21,22]. A variety of explanations of the tulip flame formation as well as several analytical models have been proposed. The possible explanations include: viscosity effect [11,21], interaction of flame with pressure wave [23], hydrodynamic instability [5,18], effect of vortex motion in the burnt region [10,22], and

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Taylor instability [4]. The experimental and analytical work by Clanet and Searby [4] suggests that both the pressure wave and boundary layer are unimportant for the tulip formation. Though the initiation of tulip flame could be caused by the hydrodynamic instability, the tulip flame formation can not be explained by the linear analysis of this instability [22,24]. Matalon and Metzener [10] thought that the actual tulip formation results from the vortical flow in the burnt gas and proposed a mathematical theory to support this mechanism. Clanet and Searby [4] pointed out that the tulip phenomenon is very similar to the inversion in Markstein's experiments [25] that is caused by the interaction between a curved flame and a shock wave. Based on this similarity, they concluded that the tulip flame formation could a manifestation of the Taylor instability. However, this mechanism has not been fully supported by an analytical theory. The numerical study by Lee and Tsai [26] indicates that the heat losses at the sidewalls of the tube have an impact on the tulip flame development. Dunn-Rankin and Sawyer [17] found that the tulip flame is sensitive to the geometry of combustion tube. Clanet and Searby [4] suggested an empirical model for the tulip flame propagation. Following this work, Bychkov et al. [2] developed a theoretical model for the early flame acceleration and tulip flame evolution, and found that the tulip flame formation does not depend on the Reynolds number.

Recent investigations [14,19,27] demonstrated that a distorted tulip flame can be produced after the full formation of a classical tulip flame during premixed hydrogen/air flame propagation in a closed tube with hydrogen concentration in the range of 26–64% by volume. A distorted tulip flame is the flame shape with two secondary cusps (distortions) formed on the two primary tulip lips, e.g. the flame at $t = 6.867$ ms in Fig. 3(b) in Ref. [14]. The onset of a distorted tulip flame coincides with the sudden deceleration of both the flame front and the pressure growth. The distorted tulip flame develops into a triple tulip front as the secondary cusps (distortions) nearly arrive at the center of the primary tulip lips [14,27]. Before the disappearance of the first distorted tulip flame, a second one can be created with a cascade of distortions superimposed on the primary lips [27]. The pressure wave (acoustic wave) triggered by the first drastic flame deceleration drives the flame front to decelerate periodically and assumes an important role in the distorted tulip flame formation [14,27]. The flame displacement speed oscillates in phase with the pressure growth rate under the effect of the pressure wave. The distorted tulip flame formation could result from the Taylor instability driven by the abrupt deceleration of the flame front [27]. Although the characteristics and mechanism of the distorted tulip phenomenon has been studied, the conditions required for the generation of a distorted tulip flame are not well understood, e.g. the effects of ignition location, tube length and heat losses at the walls.

The objective of the present work is to investigate the effects of ignition location on the premixed flame dynamics in a hydrogen/air mixture in a closed combustion vessel. Experiments are performed to examine the transient behavior and characteristics of premixed hydrogen/air flame ignited at different ignition locations. Then, the experimental results are compared with theoretical analysis to provide further knowledge of the influence of the ignition position.

Experimental approaches

The experimental setup was detailed in the earlier work [19]. It is mainly composed of a constant volume combustion tube, a gas mixing system, a high-voltage ignition system, a high-speed schlieren cinematographic system, and a synchronization controller.

The experimental combustion vessel, schematically shown in Fig. 1, is a horizontal closed duct with square cross-section 82 mm × 82 mm. The length of the duct is 530 mm. The two side panels of the tube are constructed of quartz glass to provide optical access. The rest of the walls are made of TP304 stainless steel. The temporal variations of flame shape and location in the process are recorded using the high-speed schlieren photography system. The operating speed of the high-speed video camera is 15,000 frame/s. The duct is filled with a rich hydrogen/air mixture at an equivalence ratio of 1.58 (hydrogen concentration 40% by volume). The flame in the mixture is diffusively stable and can assume both tulip and distorted tulip shapes [19]. A short time delay of about 30 s is incorporated into the gas filling process to allow a quiescent mixture before ignition. The previous studies [8,14,17] indicate that this time delay is sufficient for the mixture to become quiescent. The initial temperature and pressure inside the chamber are $T_0 \approx 298$ K and $p_0 \approx 101325$ Pa, respectively. The combustible mixture is ignited by using a single spark gap in each test. Three different ignition sites are employed in the experiments to examine the impact of ignition position on the flame dynamics, as shown in Fig. 1. The first ignition location (ignition location 1) is at the center of the left end of the duct. The second one (ignition location 2) is at a short distance off the left end wall (5.5 cm from the left end on the duct axis). The third one (ignition location 3) is in the center of the duct (26.5 cm from the left end on the duct axis). The high-speed video camera and igniter are initiated simultaneously by the synchronization controller.

Results and discussion

Development of the flame ignited at different locations

Flame ignited at the center of the left end of the tube

The development of the flame ignited at the center of the left end of the tube (ignition location 1) is shown in Fig. 2 through a sequence of high-speed schlieren images. Fig. 2(a) presents the early stage of the flame propagation while Fig. 2(b)

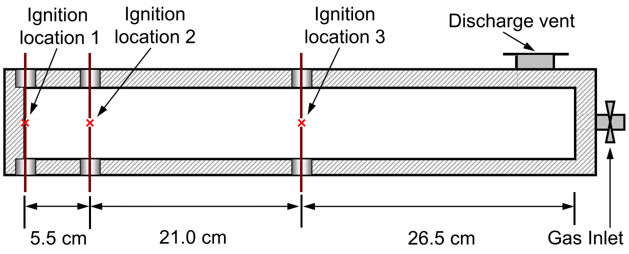

Fig. 1 – Sketch of the combustion vessel. The height of the duct is 8.2 cm.