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Full Length Article

A study on the dynamic behavior of premixed propane-air flames propagating in a curved combustion chamber

Huahua Xiao[a,*], Jinhua Sun[b], Xuechao He[c]

[a] Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, USA
[b] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230027, PR China
[c] Sichuan Fire Research Institute of Ministry of Public Security, Chengdu 610036, PR China

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ABSTRACT

Experiments and numerical simulations were performed to study the flame dynamics and pressure build-up in a curved combustion chamber filled with propane-air mixture. The configuration of the system allows a direct comparison of flame propagation in a bend to that in a straight duct. The comparison helps reveal the role of the bend in the flame dynamics. In the experiments, a high-speed schlieren system and a pressure transducer were used to record the flame evolution and pressure dynamics, respectively. In the simulations, a dynamically thickened flame (TF) model with a single-step chemistry was adopted to represent the premixed combustion. One important finding is that the bend of the chamber has a significant influence on the flame dynamics by promoting the growth of instabilities. The flame behavior in the bend is different than that in the straight section of the chamber. A salient tulip flame is formed in the bend while a much less pronounced tulip shape in the horizontal straight section. The lower part of flame dominates the burning process in the bend while the opposite is true in the horizontal straight section. Furthermore, the influence of heat transfer and gravity were examined using numerical simulations. It was found that heat transfer has an important effect on the combustion dynamics when the flame interacts with the sidewalls of the chamber. The flame propagation speed and pressure rise are overestimated in the absence of heat losses at the chamber walls. Although the gravity plays a role in the flame evolution in the straight configuration, its effect on flame dynamics is damped by the bend. The gravity effect on pressure build-up in the entire process is minor. In addition, the good agreement between the numerical simulations and the experiments supports the validity and reliability of the TF model with the one-step chemical kinetics for calculating propane-air flame propagation.

1. Introduction

Propane, generally produced as a by-product of natural gas processing and petroleum refining, is widely used as a fuel in industrial, domestic and transportation sectors [1,2]. Propane is flammable and denser than air. It can accumulate in low spaces, chambers or other confined regions, and thus poses a risk of accidental fires and explosions in its production, transportation and utilization. On the other hand, propane has also been a commercial alternative fuel for vehicles with internal combustion engines [3,4]. Understanding the combustion characteristics of propane in air is important for energy and safety applications [5–7].

Flame dynamics in chambers or tubes has given rise to a large number of studies since it represents the early development of intense explosions [8–11] and models the burning process in typical internal combustion engines [12,13]. Premixed flame propagation is an extremely complex process involving chemical kinetics, heat and mass transfer, and fluid flow. In general, a smooth laminar flame can be created by weak ignition. The laminar flame is intrinsically unstable due to various instabilities and can develop into cellular front. The flame acceleration at early stage results from thermal expansion under the confinement of the sidewalls of a tube or chamber [14,15]. After the flame reaches the sidewall, it experiences a drastic deceleration because of the rapid decrease of flame surface area. Additional flame deceleration may be caused by the heat losses to the tube walls. Lee and Tsai [16] examined the effects of heat losses through the sidewalls on the laminar flame propagation in a tube and found that the heat transfer has an impact on the flame shape. The temporary development of a tulip-shaped flame can be produced following the flame deceleration under proper conditions [14,15,17,18]. Four stages in the tulip flame propagation were distinguished in the experimental work by Clanet and Searby [15]. They proposed an empirical model for the tulip flame

* Corresponding author.
E-mail address: hhxiao@umd.edu (H. Xiao).

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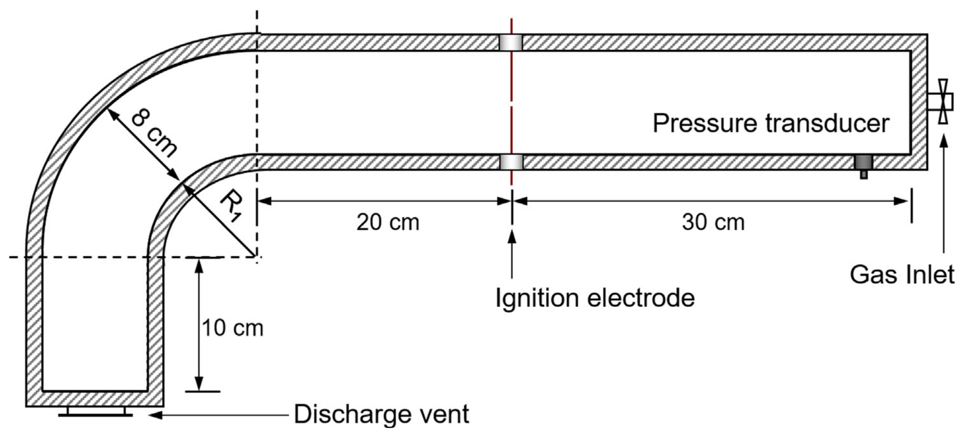

Fig. 1. Sketch of the combustion duct with a 90° bend. $R_1 = 8$ cm.

formation. On the base of this model, Bychkov et al. [14] developed an analytical theory of the early flame acceleration and tulip development. The formation of tulip flame is due to the effect of vortex motion near the flame front in the burnt gas [19,20]. Vortices are generated just behind the flame skirt near the sidewalls of tube after the flame touches the sidewalls. The vortices grow with time and overtake the leading flame front. The vortex motion consequently leads to reverse flow near the flame front in the center region of the tube. The flame front becomes inverted and a tulip-shape flame forms as the reverse flow dominates the region around the flame. The tulip flame can further evolve into distorted tulip fronts under the effect of pressure waves [19,21,22]. In a sufficiently long tube, the flame may accelerate to a supersonic regime and possibly transition to a detonation [23]. Dorofeev [24] presented a set of evaluation models of run-up distances to supersonic flames in tubes, and the critical run-up distances for the flame acceleration in hydrogen-air mixtures were evaluated.

The large majority of earlier studies focus on flame behaviors in straight tubes. However, non-straight components such as tees, bends and valves are commonly used in many pipe networks in industries. For example, gas pipelines with non-straight sections are usually employed to transport flammable gases. Moreover, if a shaped engine head (e.g., one with convex and concave surfaces) is used in an internal combustion engine, the contours will affect the combustion dynamics. Therefore, it is of importance to investigate the flame dynamics in non-straight tubes. Eearly work of flame dynamics in a curved duct was performed by Sato et al. [25] using high-speed schlieren photography and timeline tracer method. The flame shape variations and propagation speed were given in the study. They thought that the impact of bend on the flame propagation was attributed to the flow patterns in the unburned mixture preceding flame front. No tulip flame was observed in the experiment since the duct considered was a very small open duct. Tagawa et al. [26] carried out an experimental investigation on the heat transfer characteristics of a turbulent flame in a rectangular duct with a 180° curved section. It was shown that the anomalous phenomenon of counter-gradient heat transfer occurs due to the strong pressure gradient in the radial direction of the bend. The effect of a curved section on the early flame propagation was examined by Xiao et al. [27,28] using high-speed schlieren photography and numerical simulations. It was shown that the finger-shaped flame is bent in the curved section and first touches the inner wall. The flame evolves into an inclined tulip flame after it passes through the bend. The formation of the inclined tulip flame is also due to the effect of vortex motion right behind the flame front [27]. It was found that a single vortex is produced in the burnt region, and the interaction of the vortex with the flame front causes the tulip flame formation. There are still many unresolved problems in the premixed flame dynamics in curved tubes, e.g. the detailed flame front evolution, and the effects of heat loss and gravity on the combustion dynamics. In addition, whereas flames propagating either in a straight tube or a curved tube have been studied, previous research has yet to provide direct comparison of flame propagation in a bend to that in a straight duct.

In the present work, the premixed flame dynamics in a propane-air mixture in a rectangular closed chamber of strong curvature is experimentally and numerically studied. The system was designed to facilitate a direct comparison of flame propagation in a bend to that in a straight duct. The primary purpose of this work is to provide additional knowledge of flame behavior and characteristics in a curved combustion vessel. Experiments on the premixed propane-air flame propagation in the chamber are conducted using high-speed schlieren photography and pressure transducer. Then three-dimensional (3D) numerical simulations are performed using a dynamically thickened flame model and compared with the experimental results. In addition, the influences of gravity and heat losses through the chamber walls on the combustion dynamics are also examined in the numerical simulations.

2. Experimental set-up

The experimental apparatus is similar to that in our previous studies [29]. The setup is designed to allow a direct comparison of premixed flame propagation in a curved section (bend) to that in a configuration that models a straight duct. It mainly comprises a curved combustion vessel, a high-voltage ignition system, a high-speed schlieren photography system, a pressure measuring system and a synchronization controller.

The combustion chamber, closed at both ends, is schematically shown in Fig. 1. It is a constant volume rectangular duct with a 90° bend. It consists of a long horizontal straight section, a curved section, and a short vertical straight section. The cross-section throughout the combustion vessel is constant 80 mm × 80 mm. The lengths of the horizontal and vertical straight sections are 500 mm and 100 mm, respectively. The curved part is a rounded 90° bend with an external radius 160 mm and an internal radius 80 mm. A discharge vent, which only opens near the end of combustion, is set at the bottom end of the vertical straight section for safety. The side windows of the vessel are constructed of K9 glass to provide optical access. The rest of the walls are made of TP304 stainless steel. The thermal-physical properties of the walls are shown in Table 1.

The duct is filled with a premixed propane-air mixture at an equivalence ratio of 0.7. The combustible mixture is prepared using the partial pressure method and fed into the chamber from the right end of the horizontal straight section through an isolating valve. The initial temperature and pressure inside the combustion vessel are $T_0 = 298$ K and $p_0 = 101325$ Pa, respectively. A short time delay of around 30 s is incorporated into the filling sequence to ensure a quiescent mixture before ignition. A flame is initiated by a single spark gap which is