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Effect of bend on premixed flame dynamics in a closed duct

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ABSTRACT

The premixed flame dynamics and pressure build-up in a closed duct with a 90° bend are experimentally and numerically investigated, and compared to a previous analytical theory. Emphasis is placed on the effect of the bend on the flame propagation, especially on the detailed flame front evolution. The results show that the finger flame is curved along the bend. A noticeable tulip flame is produced in the horizontal straight section as the upper parts of the indented flame nearly catches up with the lower parts. The lower parts tend to dominate the flame propagation after the complete formation of the tulip flame. The tulip flame disappears with the vanishing of the upper parts near the end of combustion. The flame dynamics in the experiment is reasonably reproduced by the numerical simulations, especially with isothermal wall. It is found that the full formation of the tulip flame is accompanied by a second drastic flame deceleration arising from the rapid reduction of the surface area of the outer flame front near the outer sidewall. It is revealed that the takes on the appearance of a “trough” shape after the flame touches the outer walls. The flame is still concaved from the center toward the burnt gas after the disappearance of the tulip upper parts. The pressure rise is closely related to the flame behavior. The heat transfer through the duct walls has a significant influence on the combustion dynamics. Both the flame tip location and pressure rise in the later stages are greater in the case of adiabatic duct walls than in the experiment. The theoretical analysis demonstrates that the flame propagation mechanism in the early stages in the curved duct coincides with that in a straight duct despite the presence of the bend. However, the flame behavior after its contact with the duct sidewall and tulip formation differs from those in a straight duct under the effects of the bend.

1. Introduction

Premixed flame dynamics in tubes is of great importance since it is related to the flame acceleration in the development of detonation waves and models the burning process in internal-combustion engines [1–7]. Generally, a flame propagating in a tube is intrinsically unstable and acquires a curved shape. The flame dynamics can be influenced by various mechanisms, such as Darrieus–Landau (DL) instability, Taylor instability, acoustic waves, boundary layer, and vortical flow [2,3,8–13].

There have been numerous experimental, theoretical and numerical reports of premixed flame propagation in ducts [4,8,10,12–19]. Photographs of premixed flame propagation in closed cylinders were first published by Ellis [20], who found that the premixed flame changes suddenly from a shape convex toward the unburned gas to a backward pointing cusp in closed tubes with aspect ratio lager than two. This curious flame phenomenon is widely referred to as “tulip” flame. Dunn-Rankin and Sawyer [15] conducted a parametric experimental investigation and concluded that tulip flame formation is strongly dependant of the geometry of combustion vessel. Matalon and Metzener [10] performed a numerical study of premixed flame propagation in closed tubes based on a nonlinear evolution equation. They proposed that the formation of tulip flame is caused by vortex motion in burnt region. The numerical work also indicates that tulip formation is sensitive to mixture composition. Dunn-Rankin et al. [21] and Marra and Continillo [22] carried out numerical studies using zero Mach number model and found that the tulip flame can be produced in the absence of pressure wave effect. Clanet and Searby [8] conducted an experimental and theoretical study of tulip flame propagation. It was demonstrated in the study that both boundary layer and pressure wave are unimportant for the generation of tulip flame. And they thought that tulip flame formation results from Taylor instability. With the help of numerical simulation, Gonzalez et al. [23] suggested that wall friction is not important

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for the formation of tulip flame. Nevertheless, Marra and Continillo [22] argued that wall friction is the determining factor for the initiation of a tulip shape. It has been put into evidence that the onset of flame inversion could have a connection with DL instability [24], but the tulip flame cannot be simply explained by the linear stability analysis of DL instability. Based on the four stages of tulip flame proposed by Clanet and Searby [8], an analytical theory was developed by Bychkov et al. [14] for the early flame acceleration and the evolution of tulip flame. Moreover, a distorted tulip flame can be formed after a well-pronounced tulip flame has been established in a closed duct [12,13,18]. The distorted tulip flame develops into a triple tulip flame as its secondary cusps arrive at center of the primary tulip lips. Xiao et al. [12,13] suggested that the interaction of flame with pressure wave plays an important role in the formation of distorted tulip flame.

As remarked above, the large majority of studies are devoted to the flame dynamics in straight ducts. Nevertheless, non-straight sections such as bends and intersections are commonly used as parts of practical ducts. It is also necessary to investigate the influence of these sections on flame propagation. Sato et al. [25] carried out an experimental study of premixed flame propagation along a 90° bend in a duct. No tulip flame could be formed in the experiment because the duct was a quite small open duct. A two-dimensional (2D) numerical approach was also employed to model the gas flow ahead of the flame front. They pointed out that the flame dynamics around the bend could be primarily determined by the flow nature of the unburned mixture. Tagawa et al. [26] experimentally examined the heat transfer characteristics of a non-premixed turbulent flame in a rectangular duct with a 180° bend. The occurrence of anomalous phenomenon of counter-gradient heat transfer was demonstrated using a combined LDV and fine-wire thermocouple technique. Recently, Xiao et al. [27] experimentally and numerically studied a premixed flame propagating in a closed duct with a 90° bend. This work shows that the outer flame skirt plays an important role in the flame propagation. The flame dynamics is related to the hydrodynamics of combustion-generated flow, and the cause of a tulip flame is the motion of a single vortex behind the flame tip. However, the simplified 2D numerical model adopted in the report could not allow a sufficient investigation of the influence of the bend on flame dynamics. And it was difficult to achieve a detailed comparison between the experiment and numerical simulation by using the 2D approach. Besides, the flame evolution after the tulip formation was not presented in the study.

This paper describes an experimental and numerical investigation of premixed flame propagation in a rectangular closed duct with a 90° curved section. The purpose of this study is to further elucidate the effects of the bend on the combustion dynamics. Firstly, experiments are carried out to investigate the flame behavior and pressure build-up in the duct. Then, three-dimensional (3D) numerical simulations are conducted to provide additional knowledge of the flame dynamics and characteristics. Finally, comparisons between the prediction of an analytical theory, the experiment and the numerical simulations are performed to gain a new insight into the flame dynamics under the influence of the bend. Furthermore, the impact of heat transfer through the walls of the duct on the combustion dynamics is examined as well in the numerical simulation.

2. Experimental setup

The experimental apparatus mainly consists of a combustion chamber, a gas mixing device, a high-voltage spark ignition system, a high-speed schlieren cinematography system, a pressure transducer, a data logging system and a synchronization controller. A detailed description of the experimental setup and methodology can be found in the earlier reports [12,18]. The combustion chamber, which is schematically illustrated in Fig. 1, is a closed rectangular duct with constant square cross-section. It is composed of a short vertical section, a curved section and a long horizontal section. The cross-section of the combustion duct is 80 mm × 80 mm. The respective lengths of the vertical and horizontal straight sections are 100 mm and 500 mm. The curved section is a rounded 90° bend with internal and external radii of 80 mm and 160 mm, respectively. The side windows of the duct are made of K9 glass to allow optical viewing, and the rest of the walls are constructed of TP304 stainless steel.

The current experimental work extends the prior experiments in [27]. The combustible gas used in the experiments is a mixture of propane and air with equivalence ratio of 0.8 (expansion ratio about 7.1). The initial temperature and pressure in the duct are approximately $T_0 = 298$ K and $p_0 = 101325$ Pa, respectively. The ignition source is a single spark gap placed on the duct axis at a distance of 30 mm from the end wall of the vertical section. Bradley et al. [28] suggested that flame speed becomes independent of the effects of spark energy at a radius of 6.0 mm. In order to minimize the effects of spark igniting energy, a short time delay of 2.0 ms is incorporated into the recording process of the high-speed schlieren system after spark discharge. The experiment tests showed that this time delay can approximately allow the flame to propagate spherically over a distance of 6.0 mm. The variations in flame shape and position with time during the combustion process is recorded using the high-speed schlieren device. A high-speed video camera FASTCAM Ultima APX is used and a framing speed of 2000 frame/s is chosen. Pressure–time history inside the vessel is obtained using a transducer (PCB Piezotronics model 112B10) located at the bottom of the horizontal section 30 mm from the right end wall of the vessel. The spark igniter, data recorder, and high-speed video camera are initiated by the synchronization system. The experiment is repeated five times to ensure the reproducibility. The flame shape, arrival times and pressure rise are demonstrated to be pretty reproducible.

3. Numerical methods

3.1. Governing equations

It has been put into evidence that the flow generated by the transient combustion in a laboratory-scale smooth tube is substantially laminar [2,12,29]. The flame propagation is simulated here as a 3D laminar reacting flow. The governing equations are the compressible Navier–Stokes (N–S) equations together with the mass, energy and species conservation equations:

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

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

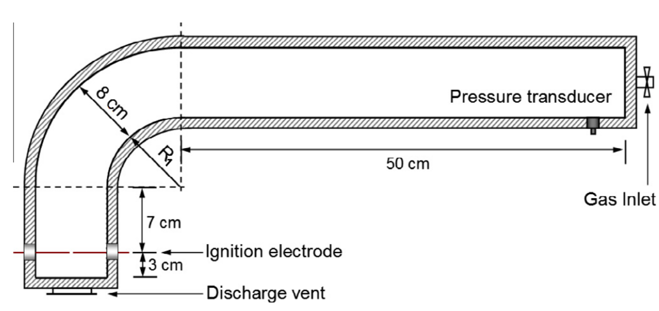

Fig. 1. Schematic of the premixed combustion vessel [27]. R_1 = 8 cm.