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Technical Note

# Experimental and numerical study of premixed flame propagation in a closed duct with a 90° curved section

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ABSTRACT

The premixed flame propagation in a closed duct with a 90° bend is studied using high-speed schlieren photography and numerical simulation. The investigation provides basic understanding of the influence of the bend on the premixed flame propagation. The flame undergoes four stages in the propagation. The outer flame skirt influences significantly the flame dynamics. The flame surface area reaches its minimum value after the full formation of tulip flame. The flame dynamics observed in the experiment is well reproduced by the numerical simulation. The flame behavior at the later stage is in close connection with the hydrodynamics of the combustion-generated flow. The numerical simulation indicates that a single vortex is generated near the flame tip in the burnt gas just before the formation of flame indentation. The vortex remains in the vicinity of the flame tip and changes the flow field around the flame front. As a consequence, the effects of the circulating flow create the conditions required for the formation of a tulip flame.



## 1. Introduction

Flame propagation in tubes is one of the important subjects of fundamental investigation [1–9]. It has given rise to a large number of studies and numerous significant advances have been made in the understanding of flame dynamics [1,2,6–15]. Ellis [10] found that the flame develops into a tulip shape in closed tubes with aspect ratio >2. The formation of tulip flame depends on the composition of the flammable mixture and the geometry of combustion chamber [3,5]. The numerical investigations [2,4] indicates that the tulip flame can form without pressure wave effects. The study by Clanet and Searby [1] demonstrates that neither pressure wave nor boundary layer are important for the tulip flame development. Gonzalez et al. [11] concluded that wall friction is not dominant in the tulip flame formation. Following the acceleration mechanism proposed in [1], Bychkov et al. [12] developed a theoretical model of flame acceleration and tulip evolution. Furthermore, another interesting observation in a closed duct is that a distorted tulip flame can be produced after the full formation of a tulip flame [13]. Most of the studies focus on the flame propagation in straight ducts. However, practical ducts commonly include non-straight sections, e.g. bends and T-junctions. Therefore, there is also a requirement for understanding the effects of these sections on flame dynamics. Sato et al. [14] conducted an experimental and numerical investigation of flame propagation in a small-scale open square duct with a 90° bend. It was found that the flow pattern can be correctly reproduced in two-dimensional (2D) numerical simulation in the absence of secondary flow. However, no tulip flame was observed in the study. Zhou et al. [15] investigated the impact of a 90° bend on the very later stage of flame propagation in a closed duct, i.e. the stage after the tulip flame has been fully formed, based on experimental measurements and numerical simulation. They suggested that the flame tends to avoid contact with the inner and outer walls when it propagates in the bend.

In the present work, the premixed flame propagation in a closed duct with a 90° bend is experimentally and numerically studied. The influence of the bend on flame dynamics in the early stages is examined. The main objective of this study is to provide further knowledge of the flame dynamics in a curved duct.

## 2. Experimental apparatus

The experiments on propagating propane/air flames are carried out with an apparatus pretty similar to our earlier work [13]. The combustion vessel, which is schematically illustrated in Fig. 1, is a closed duct with constant square cross-section 8 cm × 8 cm. It comprises a 90° curved section, a horizontal straight section (50 cm long) and a vertical straight section (10 cm long). The internal and external radii of the bent section are 8 and 16 cm, respectively. The side panels of the duct are constructed of K9 glass

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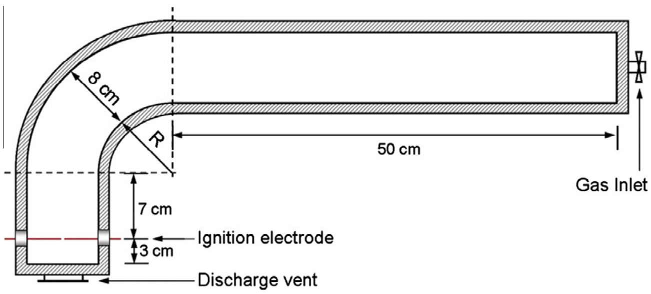
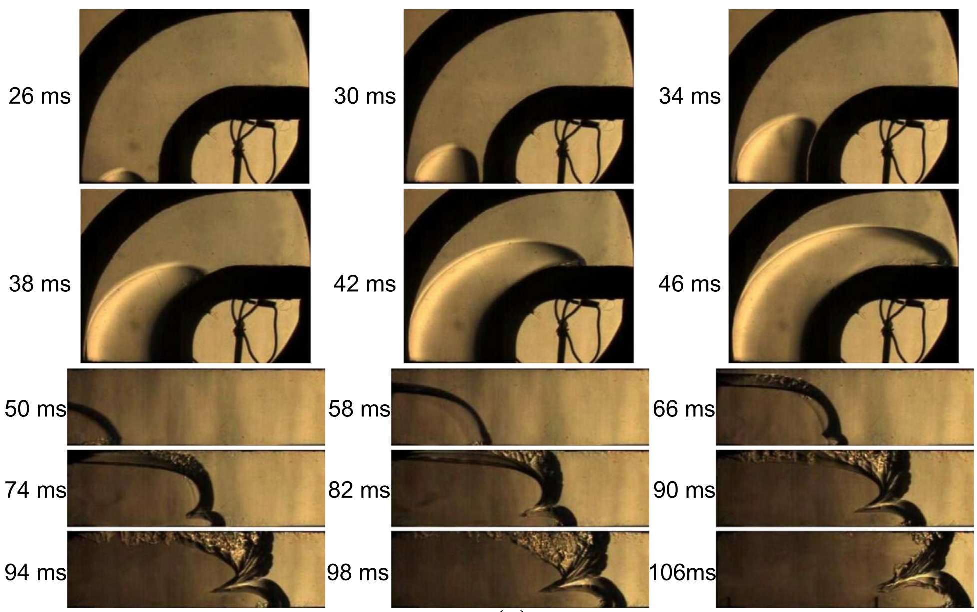
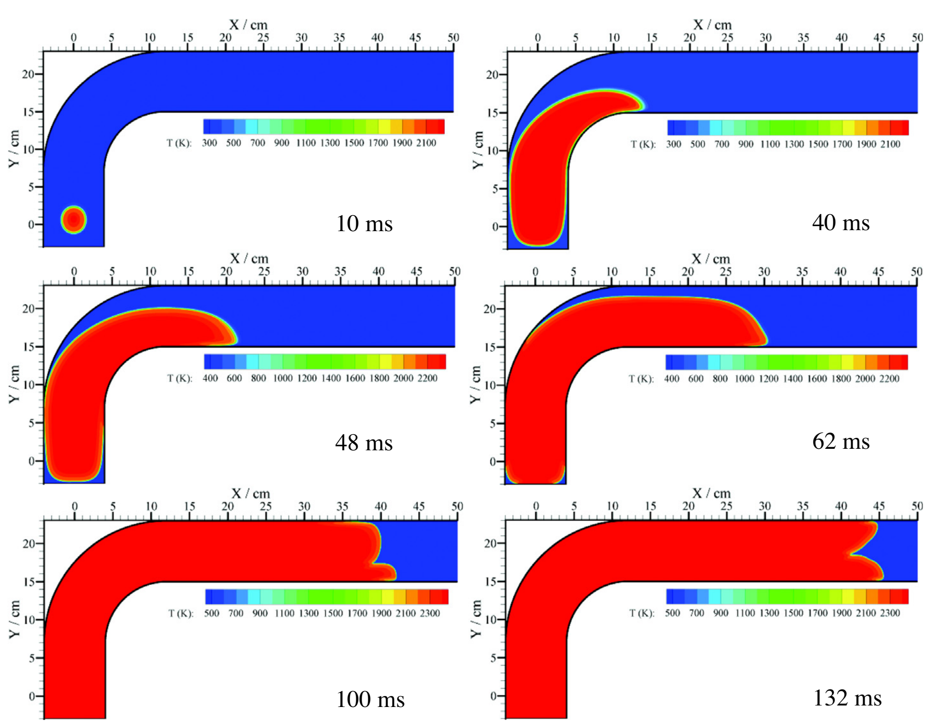



**Fig. 1.** Schematic diagram of the experimental combustion duct. $R$ = 8 cm.

to provide optical access. The duct is filled with a premixed propane/air mixture (equivalence ratio 0.8) through an isolating valve. The initial pressure and temperature are $p_0$ = 101325 Pa and $T_0$ = 298 K, respectively. The mixture in the duct is allowed to settle before ignition and the settling time is 30 s [3,13,16]. The mixture is ignited by a single spark gap located on the duct axis 3 cm from the endplate of the vertical section. The changes in flame shape and position with time is recorded using a high-speed schlieren device. The schlieren photography could provide more details of the flame dynamics than the CCD camera used in [15], e.g. the flame instabilities and the flame behavior near/along the duct sidewalls. A framing rate of 2000 frame/s of the high-speed video camera is used.




**(a)**




**(b)**

**Fig. 2.** (a) High-speed schlieren images of premixed propane/air flame. (b) Evolution of the numerical flame. Temperature distribution from unburned (blue) to burnt (red) gases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)