Combustion and Flame 161 (2014) 1558–1565

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Initiation and formation of the corrugated structure leading to the self-turbulization of downward propagating flames in a combustion tube with external laser absorption

Yoshikazu Taniyama, Osamu Fujita *

Hokkado University, Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido, Japan

ARTICLE INFO

Article history:
Received 31 August 2013
Received in revised form 17 November 2013
Accepted 2 December 2013
Available online 20 December 2013

Keywords:
Laminar flame
Combustion tube
Acoustic instability
External laser irradiation method
Transition to turbulent motion

ABSTRACT

Combustion tube (length 45 cm, inner diameter 5 cm) experiments with flames of premixed gas of C_2H_4/CO_2–O_2 (Le < 1) were conducted. The flame fronts propagated downward to the closed bottom of an open-ended tube. An initially steadily propagating flat flame was deformed by an external laser irradiation method to investigate its evolution under the interaction with acoustic vibration. Results showed that the locally deformed flame evolved into a corrugated structure at the flame front followed by self-turbulization. The process to form this corrugated structure was investigated in detail based on the images captured using high-speed cameras. From the observations, a possible mechanism for the initiation of the corrugated structure, explained mainly by periodic acoustic acceleration, was proposed. Then, according to the mechanism an alternative definition for the inverse Froude number is proposed in this work and used as criterion for the initiation of the corrugated flame structure. To prove the validity of the criterion two mixtures having different flame speed were tested and it was confirmed that the criterion provided transition condition very well for both tested mixtures.

1. Introduction

Interactions between flames and acoustic fields are one interesting research topics in combustion. In industrial applications such as gas turbines, rocket engines, etc. flame and acoustic interactions can often lead to extremely strong acoustic oscillation associated with self-turbulization. When flames propagate in tubes or other confinements, acoustic waves are generated and, in some conditions, they are extremely enhanced as a result of heat release rate fluctuation in phase with pressure fluctuation.

Research on such phenomena has been conducted for more than a century [1–8] and some flame instability mechanisms affecting the phenomena have been previously studied; for example, hydrodynamic instability [9–11], thermal diffusive instability [12,13], and body-force instability referred as the Rayleigh–Taylor instability [14–16]. In addition to them, interaction between flame and acoustic waves has been discussed according to the Rayleigh criterion [17], where it is noted that if changes in heat release are in phase with the acoustic waves, the thermal energy will amplify the acoustic waves.

Searby [3] reported the general flame behavior of downward propagation in a half-open tube. Four distinct regimes leading to self-turbulizing flame after the fulfillment of Rayleigh criteria were reported: (1) a softly curved shape induced by the hydrodynamic instability just after ignition, (2) a planar shape stabilized by the primary acoustic instability, (3) a secondary acoustic instability associated with pulsating cellular structure, and (4) transition to complete turbulent motion. Searby and Rochwerger [4] proposed a theoretical instability diagram to predict the condition of self-turbulization of downward propagating flames in tubes by applying the linear stability theory of plane flame proposed by Clavin and Garcia [5]. Experimental verification for the diagram was provided, however, the transition process from the primary to the secondary instability was not elucidated in full detail. According to the description in Ref. [4], once the flame is in the regime of the secondary instability, a pulsating cellular structure suddenly appears and transitions to the turbulent motion. However, it was not established how the pulsating cellular structure is initiated from a perturbation originally existing in the flow and how it distributes over the propagating front as observed in Searby's work [3].

In our previous study, Tsuchimoto et al. [6] proposed a novel technique to control local flame structure, called CO_2 laser irradiation method. They investigated the oscillating motion of an upward propagating flame in a tube using the CO_2 laser irradiation method which forms convex flame surface with desired dimension towards the unburned mixture. The fuel used in their study was ethylene, which absorbs CO_2 laser light sufficiently to increase

* Corresponding author. Fax: +81 11 706 7841.
E-mail address: ofujita@eng.hokudai.ac.jp (O. Fujita).

0010-2180/$ - see front matter © 2013 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.combustflame.2013.12.002

the local temperature and local combustion velocity of the irradiated region. The local change of the combustion velocity can be used to attain a desired flame deformation causing an oscillating motion of the flame front. Park et al. [7,8] have conducted experiments on the downward propagating flames and suggested that a CO_2 laser method could control the initiation of the transition from the primary to the secondary instability followed by the self-turbulization. In their research, the focus was only on the growth process of the initial single cell structure by the CO_2 laser method termed regime 1 in [8] and there was no discussion on the formation of the pulsating cellular structure (called as corrugated structure in the present work) followed by the transition to turbulent motion.

In the present paper, a short-term CO_2 laser irradiation method was applied in order to discuss the relationship between the initial deformed shape (initial perturbation) and transition to the corrugated flame (secondary acoustic instability). We observed the transition process of downward propagating flames in a tube. In particular the focus was on the transition from the deformed single cell to the corrugated flame, which has never been reported in detail. A discussion on the transition criteria is made and the newly defined Froude number, called the pulsating Froude number, is proposed as a criterion for the onset of the transition to the secondary instability followed by the turbulent motion.

2. Experimental configuration

A schematic of the experimental setup is shown in Fig. 1a. An acrylic propagation tube, 45.0 cm long and 5.0 cm inner diameter is fixed parallel to the direction of gravity. The premixed gas composed of ethylene, oxygen, and carbon dioxide is set at atmospheric pressure in the tube. Ethylene gas plays an important role as the main absorption medium of CO_2 laser light according to the NIST chemical database [18]. Carbon dioxide was used as an inert gas to decrease the burning velocity, allowing detailed time-resolved observations. The mixture is ignited by a spark plug located near the upper end of the tube and the flame front propagates downward. Right before ignition, the upper end of the tube is opened by the combined action of four electro-magnetic and mechanical springs. The CO_2 laser beam (beam diameter 3.3 mm, SYNRAD Firestar v20, wave length 10.6 μm) passes vertically along the center of the tube. Laser irradiation period is controlled using a mechanical shutter, laser exposure starts at 800 ms after activating the spark igniter and then the CO_2 laser beam preheats the unburned mixture just ahead of the flame front along the center line. The flame oscillatory behavior is captured using two high-speed cameras, IDT MotionPro X-4 and nac HSV-500C[3] recording at 3200 and 500 fps respectively. The elongation, H, shown in Fig. 1b is measured to characterize the deformation size induced by the laser irradiation. The moment of laser exposure start is defined as $t = 0.0$ ms in the present study. Pressure temporal variation is measured with a PCB Piezotronics 106B52 dynamic pressure sensor located at the bottom end of the tube and sampling at rate 10 kHz.

In this paper, we tested two mixtures at given compositions (see Table 1). The main difference between two gas mixtures is their laminar burning velocity as calculated using CHEMKIN (Primex code/ GRI-mech 3.0) [19]. The laminar flame velocity for mixture A is 4.8 cm/s faster than that of mixture B. The adiabatic flame temperatures are different between two mixtures as well as the laminar flame velocity. For mixture A, a steady quasi-planar flame, as shown in Fig. 2b-1 is formed near the middle of the tube and then propagates to the end of the tube. On the other hand, for mixture B a steady cellular flame propagates slower as shown in Fig. 2c-1. This cellular flame formation can be explained by the effect of gravity [20,21]. The averaged flame propagating speed in tubes without laser irradiation are 15.9 cm/s of mixture A and 13.0 cm/s of mixture B. The ratio of calculated value of laminar flame speed coincides with the ratio of flame propagating speeds measured in the experiments.

In this study, the laser power and irradiation time are controlled as experimental parameters. The laser exposure accelerates the flame front locally at the center of the flame front. The different local burning velocity can result in a deformed flame, which is convex toward the unburned mixture region. The size of initial deformation can be determined by changing these parameters.

Table 1
Gas components and properties for mixture A and B.

Label	Mixture components			Mixture properties			
	C_2H_4 (%)	O_2 (%)	CO_2 (%)	Le	Φ	S_L	T_b
A	9	21	70	0.840	1.29	25.1	1930
B	9	20	71	0.834	1.35	20.3	1833

%: Volume, Φ: equivalence ratio, Le: Lewis number, S_L: 1 – D laminar burning velocity(cm/s, CHEMKINPro, Premix Code, GRI-Mech3.0), T_b: adiabatic flame temperature (K, CHEMKINPro).

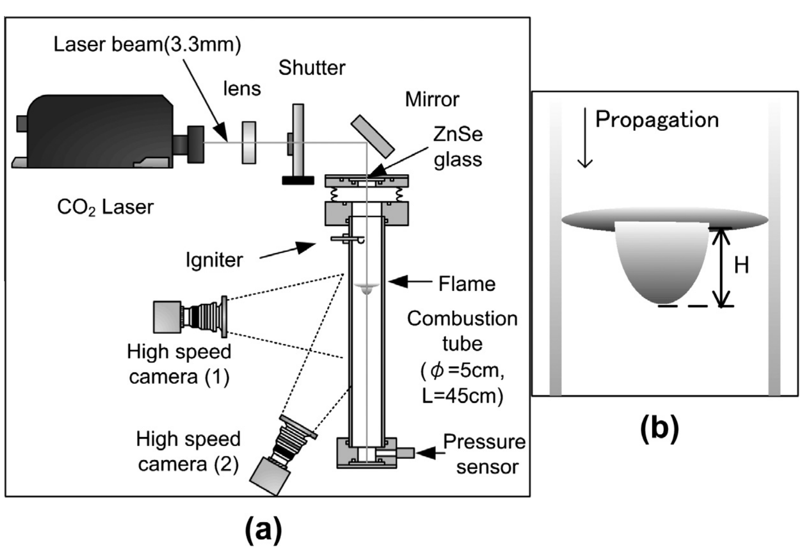

Fig. 1. (a) Schematic of experimental setup (b) conceptual description of deformed flame induced by laser irradiation propagating downwardly in a tube.