Combustion and Flame 186 (2017) 140–149

Contents lists available at ScienceDirect

Combustion and Flame

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

Direct estimation of edge flame speeds of lifted laminar jet flames and a modified stabilization mechanism

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ARTICLE INFO

Article history:
Received 21 March 2017
Revised 19 May 2017
Accepted 11 August 2017
Available online 5 September 2017

Keywords:
Lifted flame
Edge flame
Flame speed
Flame stabilization
Schmidt number

ABSTRACT

The flame stabilization mechanism of a lifted flame in a laminar fuel jet has been explained based on the edge flame concept. Previous studies have employed a similarity solution between velocity and fuel concentration, and showed that a lifted flame can be stabilized when the Schmidt number, *Sc*, is within a range of either $Sc > 1$ or $Sc < 0.5$. However, two unsolved problems remained, and they were mainly answered in this study. First, the edge flame speed could not be determined from the similarity solution using the experimental results of stable lifted flames. To resolve this, the experimental relationship between the fuel flow rate and the liftoff height was measured with a higher resolution, and a new method employing an effective Schmidt number was suggested. As a result, the relationship between the edge flame speed and the fuel concentration gradient could then be directly estimated from the simple experimental values for flow rate and the liftoff height. This new method was validated for various experimental parameters including the tube diameter, air-premixing ratio, and nitrogen-dilution ratio. Second, the reason why a stable lifted flame was not obtained when $Sc < 0.5$ could not be explained theoretically. Here, the existence of a unique criterion of $Sc > 1$, for a stable lifted flame was clarified theoretically. This study will advance understanding of the characteristics and stabilization mechanism of lifted edge flames in laminar non-premixed fuel jets.

1. Introduction

In 1965, Phillips first observed an interesting flame structure within a stratified methane-air mixing layer [1]. It had three flame branches: a lean premixed flame, a rich premixed flame, and a diffusion (or non-premixed) flame in the downstream. The propagation speed of this flame was much faster than the laminar burning velocity (LBV) of a stoichiometric mixture, and it increased as the thickness of the mixing layer grew. Almost two decades later, Ishikawa [2] observed similar unsteady flame structures in an experiment on ignition within a stratified fuel–air mixing layer. Dold [3] explained that these flame structures play key roles not only in stabilizing the lifted flames but also in the turbulent flame's propagation. This flame structure was later variously called a triple flame, a tribrachial flame, or an edge flame.

A representative study of the phenomenon using a laminar fuel jet from a small-scale contraction nozzle (with an inner diameter of 0.164, 0.195, or 0.247 mm) was conducted by Chung and Lee in 1991 [4]. The stabilization mechanism of the lifted flames was explained using the similarity between two equations for the velocity and the fuel concentration. They described the stabilization mechanism using the Schmidt number, which is defined as the ratio of kinematic viscosity to mass diffusivity, $Sc \equiv \nu/D$, and insisted that the lifted flames could be theoretically stabilized when $Sc > 1$ or $Sc < 0.5$. A number of experimental studies showed that stable liftoff flames existed when $Sc > 1$. However, the other stabilization condition of $Sc < 0.5$ was not observed experimentally. In practice, hydrogen flames could not be stabilized as a lifted flame, and the excessive mass diffusion at the nozzle exit was suspected to be the main reason [4]. Nevertheless, it was questionable why this practical instability corresponding to $Sc < 0.5$ could not be explained theoretically.

In further investigation, the relationship between the fuel concentration gradient (FCG or $\partial Y_F/\partial r$) and the edge flame speed (EFS or S_{edge}), denoted hereafter as the EFS/FCG relationship, has been of particular interest. Because the FCG is a main parameter that governs the edge flame's curvature and scalar dissipation rate, the EFS/FCG relationship has been pursued in studies on combustion dynamics and turbulent flames. Although Phillips had reported a similar trend [1], a direct EFS/FCG relationship was first explored by Kioni et al. in 1993 [5]. They used a system consisting of a multi-slot part and a diverging channel connected at the downstream. They measured the flow rate, fuel concentration, and flame location in the diverging channel. The EFS was defined as the

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http://dx.doi.org/10.1016/j.combustflame.2017.08.007
0010-2180/

Nomenclature

d_i	tube inner diameter
d_o	tube outer diameter
i	velocity profile index
Q	flow rate
r	radial distance
r^*	radial distance of a lifted flame
R	tube inner radius
S_L^0	un-stretched laminar burning velocity
S_{edge}	edge flame speed
Sc	Schmidt number
$\overline{Sc}$	average Schmidt number
$\widetilde{Sc}$	temporary Schmidt number
Sc'	perturbation of Schmidt number
Sc^*_{eff}	effective Schmidt number
T	temperature
u	velocity in the stream wise direction
u^*	flow velocity at the lifted flame
$\bar{u}_e$	average velocity at tube exit
x	stream wise distance
x^*	liftoff height
Y_F	fuel mass fraction
$Y_{F,\ e}$	fuel mass fraction at the tube exit
$Y_{F,\ st}$	stoichiometric fuel mass fraction
Greek	
D_{FA}	binary diffusivity between fuel and air
ν	kinematic viscosity
ρ_u	density of unburned mixture
ρ_b	density of burned gas mixture
ξ	similarity variable
Subscript	
F	pure fuel or fuel side
FA	fuel and air mixture
FN	fuel and nitrogen mixture

average flow velocity of the cold flow at the location of the flame front. The EFS was much faster than the LBV of the stoichiometric mixture, but the EFS/FCG relationship was not clear. Ruetsch et al. [6] analytically explained that the EFS was faster than the LBV mainly due to the flow re-direction in the upstream of the flame. Thus, the EFS would reach its maximum at the smallest FCG, as follows:

$$S_{edge,\max} \propto S_L^0\sqrt{\rho_u/\rho_b}. \tag{1}$$

Here S_L^0 is the LBV of an un-stretched stoichiometric flame, and ρ_u/ρ_b is the density ratio of the unburned to burned mixtures.

Various experimental cases were explored by the Chung's research group, including the effects of fuel-dilution [7] and air-premixing [8] on the liftoff heights. In a detailed study on flame stabilization by Lee and Chung [9], it was shown that the flow velocity in the upstream of the lifted flame was larger than S_L^0. In addition, a representative result of the EFS/FCG relationship was obtained by Ko and Chung [10] for unstable methane flames ($Sc < 1$). They used a fuel tube (d_i= 2.08 mm) relatively larger than those used in the previous studies [4,7–9]. Using a high-speed camera, they recorded unsteady flame propagation to the tube tip after ignition at the downstream with a high-power laser. The relative flame speed to the theoretical cold flow velocity was defined as the EFS, and the FCG was estimated partly from the experimental results. Using this data, the EFS/FCG relationship was derived for methane flames, and it was shown that EFS decreases monotonically with the increase in FCG.

The EFS/FCG relationship hidden within the stable lifted flame was partly extracted through a numerical study conducted by Chen and Bilger [11]. The non-reactive flow velocity and species concentration were solved numerically for the same conditions of the previous experiment [4] regarding the stable lifted propane–air flames. Using the local flow velocity at the liftoff height, some results comparable to the EFS/FCG relationship could be extracted. However, it was a formidable task to determine the various EFS/FCG relationships using this method, because every experimental condition required an additional respective numerical simulation.

A few years later, the same method used in the previous study for methane [10] was applied to measure the EFS/FCG relationships for propane flames [12]; i.e., the unsteady flame propagation after ignition was recorded using a high-speed camera, and the EFS was estimated at the conditions of lower flow rates. It is notable that lifted flames could also be stabilized at higher flow rates because a small tube diameter (d_i= 0.254 mm) was used in that study. The structures of lifted stable flames were investigated at higher flow rates independently [13]. Nevertheless, unstable propagating flames at lower flow rates were used to measure the EFS [12]. A similar experiment was conducted again to investigate the effects of velocity gradient, and improved experimental results for the EFS/FCG relationship was reported [14]. Later, some of those results will be compared with the results from this study. A number of studies have been conducted to investigate lifted flames, and they have been summarized in review papers [15,16].

In addition to the small jet experiments, the EFS/FCG relationships were directly measured for methane and propane flames using an improved multi-slot-burner with a contraction nozzle; i.e., in an open space [17], within a diverging channel [18], and with fuel dilution [19]. It was shown that the EFS has a turning point at a small critical FCG, and this was proposed to be the criterion that distinguished a premixed edge flame from an ordinary diffusion edge flame. When the FCG was larger than the critical value, an ordinary trend was obtained, and the EFS decreased as the FCG grew. Some results from the open space study [17] will be compared with the results of this study. However, the burner used in [17–19] was not suitable for producing a larger FCG, which might be more important in turbulent combustion studies.

To construct abundant database and knowledge related to the structures of edge flames, an efficient method is needed that can extract the EFS/FCG relationship from various stable lifted flames. In addition, an analytical explanation is also necessary to address why the theoretical stabilization condition of $Sc < 0.5$ could not be observed in practical experiments. In this study, therefore, the connections between experimental results and similarity solutions were investigated. 1) The liftoff heights of propane flames were measured again with a higher order of resolution for various parameters including the tube diameter, air-premixing ratio, and nitrogen-dilution ratio. 2) The analytic method was improved so that the EFS/FCG relationship could be extracted from the similarity solution just by using the simple experimental values for the flow rates and liftoff heights. 3) A unique stabilization criterion for a lifted laminar jet flame, $Sc > 1$, was derived theoretically, and the ambiguous criterion of $Sc < 0.5$ could be eliminated.

2. Experiments

2.1. Experimental methods

A schematic of the experimental setup, which is similar to those used in previous studies, is shown in Fig. 1. Three fuel-tubes were used, after polishing their end-tips. The outer diameters were measured with a micrometer gauge and the inner diameters were