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Tip opening of premixed bunsen flames: Extinction with negative stretch and local Karlovitz number

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ABSTRACT

The characteristics of tip openings in premixed bunsen flames have been studied experimentally by measuring OH radicals from laser-induced fluorescence and tip curvatures from chemiluminescent images. Results showed that the tip opening occurred at a constant equivalence ratio and was independent of the jet velocity in propane/air mixtures. The observation of a local extinction phenomenon of the negatively stretched flame due to the flame curvature could not be consistently explained based on flame stretch or the Karlovitz number, since they varied appreciably with the jet velocity. The concept of the local Karlovitz number ($\mathrm{Ka_L}$) was introduced, which is defined as the ratio of the characteristic reaction time in the normal direction for a stretched flame to the characteristic flow time in the tangential direction for the stretched flame. The local Karlovitz number maintained a constant value under tip opening conditions, irrespective of the jet velocity. Tip opening occurred at a reasonably constant local Karlovitz number of about ~1.72 when the nitrogen dilution level in propane and n-butane fuels was varied.

1. Introduction

In understanding the behaviors of flames, the aerodynamic effect of the flow field as characterized by flame stretch has been recognized as a key factor. In an invariant form, a flame stretch, κ [$\mathrm{s^{-1}}$], consists of a non-uniform tangential velocity gradient along the flame surface and the curvature of the propagating flame [1–4]. The flame stretch is often non-dimensionalized with the characteristic reaction time, $S_{L,0}/\delta_0$, to an unstretched one-dimensional flame, which results in the Karlovitz number, Ka, where $S_{L,0}$ is the laminar burning velocity of the unburned side and δ_0 is the flame thickness. When adopting $\delta_0 = \alpha_0/S_{L,0}$, the Karlovitz number becomes $\mathrm{Ka} = \kappa/(S_{L,0}/\delta_0) = \kappa/(S_{L,0}^2/\alpha_0)$, where α_0 is the thermal diffusivity.

The preferential diffusion effect from the imbalance of thermal and mass diffusions, represented by the Lewis number, Le, also appreciably influences the behavior of flames particularly the flame speed and extinction. Thus, stretched premixed flames can exhibit different behaviors depending on the Lewis number and the positive/negative stretch [5,6]. Counterflow flames [7–16], as a canonical flame representing positive stretch, and the tip opening behaviors of bunsen flames [17–23], representing negative stretch, have been extensively studied to characterize the effect of flame stretch on the propagation and extinction of premixed flames. Such characteristics can be related to the laminar flamelet model of turbulent premixed flames [24].

As the positive stretch increases, the flame speed, S_L, is influenced by both stretch and preferential diffusion and is typically correlated as $S_L/S_{L,0} = 1 + \mathrm{Ma} \times \mathrm{Ka}$, where the Markstein number, Ma, can vary from positive to negative values depending on the fuel. At excessively large stretch, the reduction in the characteristic flow time weakens a flame and eventually the flame can be extinguished. It has been reported that the stretch or the Karlovitz number [25,26] at flame extinction in counterflow flames varies significantly depending on the fuel, equivalence ratio, initial temperature, and initial pressure.

In premixed bunsen flames, flame extinction can be localized at the tip of the flame, where the negative stretch rate has its maximum along the flame front. A tip opening phenomenon has been observed for fuels with Le smaller than unity. Experimental results showed that the tip opening occurred at a constant equivalence ratio (5.7% and 31.6% in a volume of fuel mixed with air for rich propane and lean hydrogen, respectively), regardless of the jet velocity [17,18].

The flame stretch of a bunsen flame tip is proportional to $\overline{U}/R$ [4], where $\overline{U}$ is the average jet velocity and R is the radius of the curvature at the flame tip. As the jet velocity increases, the stretch

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increases sharply because the radius of the curvature decreases. Because the unstretched characteristic reaction time ($S_{L,0}^2/\alpha_0$) is fixed at a specified equivalence ratio, the nature of the tip opening irrespective of the jet velocity raises a question about the role of flame stretch or the Karlovitz number on the local extinction behavior at the flame tip.

The motivation of the present study is to elucidate the effect of negative stretch on the local extinction of tip opening in premixed bunsen flames. In this regard, the local Karlovitz number concept [26,27] will be introduced in analyzing the tip opening behavior. This concept has been adopted previously in explaining the extinction behavior of counterflow premixed flames.

2. Experiment

The experimental setup consisted of a coflow burner, flow controllers, a digital camera, and various laser diagnostic systems for OH radicals, velocity, and temperature. The coflow burner had a central tube made of stainless steel with an inner diameter, D, of 7.53 mm and a wall thickness of 1.00 mm. To ensure that parabolic velocity profile was fully developed in the tube up to the maximum velocity tested in the present experiment, the length of the tube, L, was set to 470 mm, satisfying the fully developed condition of $L/D > 0.06 \times \mathrm{Re}$ [28]. Here, Re is the Reynolds number based on D, the average jet velocity, $\overline{U}$, and the kinematic viscosity of the fuel/air mixture. The coflow air was supplied to minimize external disturbances through a coaxial nozzle with a diameter of 92 mm. A layer of glass beads and a ceramic honeycomb were stacked in the coflow nozzle to obtain a reasonably uniform velocity profile. The coflow velocity was fixed at 5 cm/s. Methane (CH_4, 99.95%), propane (C_3H_8, 99.5%), and n-butane (n-C_4H_{10}, 99.5%) were used as fuels, and compressed air was used for the oxidizer and coflow, unless otherwise specified. Mass flow controllers calibrated with dry-test gas meters regulated the flow rates.

The PLIF setup consisted of a pulsed Nd:YAG laser (Continuum, Powerlite DLS 9010), a dye laser (Continuum, ND6000), and a frequency doubler (Continuum, UVT-3). The $Q_1(6)$ transition ($A^2\sum^+ - X^2\Pi$ (1, 0) band at 282.96 nm) for OH was selected for the excitation. An intensified charge-coupled device camera (ICCD; Princeton Instruments, PI-MAX3 1024i), together with a UV lens was used to capture the OH fluorescent signal with a set of optical filters (WG305 and UG11). A particle image velocimetry (PIV, LaVision, FlowMaster) was used to characterize flow-fields. In addition, a Coherent anti-Stokes Raman spectroscopy (CARS) system was used to measure temperature profiles. A pulsed Nd:YAG laser (Continuum, Surelite II-10) and a broadband modeless dye laser were used to produce N_2 CARS signal in a folded boxcars phase-matching configuration. A lens of $f = 100$ mm was used to generate CARS measuring volume with two Nd:YAG laser and one dye laser beams. The measuring volume of the CARS was calculated to be 2.1×0.03 mm. Details of CARS measurement was reported previously [29,30].

The process for determining the radius of the curvature of a flame tip was as follows (Fig. 1). From a flame image captured by a digital camera (a), the locus of maximum signal intensity along a vertical direction was extracted (b). An ellipse, which best fit to the tip region, was drawn and the coordinates along the ellipse around the tip were extracted. These data were fitted by a function, $f(x) = ax^2 + bx + c$, where x is the horizontal coordinate. The radius of curvature was calculated by $R = [1 + f'(x)^2]^{3/2}/|f''(x)|$. At the flame tip ($x = x^*$), $f'(x^*) = 0$ due to axisymmetry, and $f''(x^*) = 2a$. Thus, the radius of the curvature at the flame tip could be determined as $R = 1/2|a|$ (c).

The pathlines of the seed particles (TiO_2, nominal size ~1 μm) are shown in Fig. 1d by using a sheet beam from an Ar-ion laser (Spectra-Physics, Stabilite 2017). The pathlines were aligned in the axial direction and started to bend by gas expansion when crossing the flame region.

3. Results and discussion

3.1. Tip opening visualization

Figure 2 shows four series of premixed flame images, which were taken at fixed exposure time (1/40 s and 1/100 s for methane/air and propane/air flames, respectively). Variations in flame shape and color, due to a change in the equivalence ratio, ϕ, can be observed in the methane/air (a) and propane/air (b) mixtures, respectively, at fixed $\overline{U} = 100$ cm/s. To highlight the condition of the tip opening of the propane/air flames, two equivalence ratios were chosen at $\phi = 1.4$ (c) and 1.5 (d) at various $\overline{U}$.

In methane flames (a), the flame tips can be clearly identified at $\phi \geqslant 0.9$. At $\phi = 0.8$, the range of $\overline{U}$ for stable flames was narrow at 23.6–49.7 cm/s [31,32]. At $\phi \leqslant 0.7$, no stable flame could be observed, which was consistent with previous studies [32].

The flame color of the propane flames with fixed $\overline{U}$ (b) changed from blue to greenish-blue as the mixture became richer. The luminosity at the tip became weaker as the mixture became richer. At $\phi = 1.5$, the flame clearly had a tip opening, and the opening region enlarged when the mixture was $\phi = 1.6$. However, the influence of $\overline{U}$ on the tip opening was minimal based on the comparison of (c) and (d). All the flames show tip opening behaviors at $\phi = 1.5$, while all the flames at $\phi = 1.4$ have the tips closed. These results suggest that tip opening occurs at a certain equivalence ratio between $\phi = 1.4$ and 1.5 and is thus relatively insensitive to $\overline{U}$.

To understand this tip opening phenomenon, we studied the PLIF images of the OH radicals. Those corresponding to the flames in Fig. 2 are shown in Fig. 3. Each image was averaged over 20 instantaneous shots. After subtracting the background noise and correcting with the laser beam profile, the images in Fig. 3a and b were normalized with the maximum OH intensity at $\phi = 0.9$ for

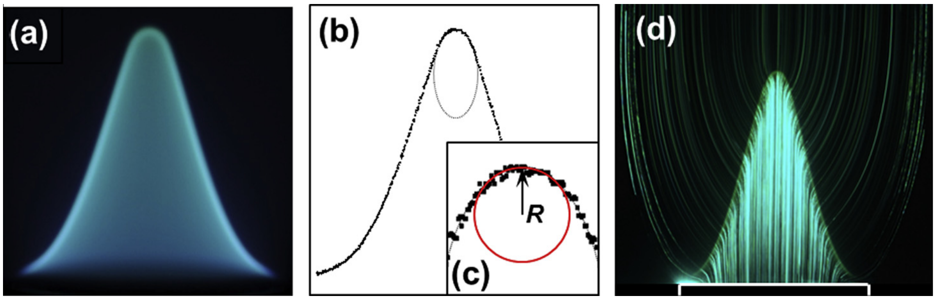

Fig. 1. Method to determine the radius of curvature at the flame tip, (a) direct flame image, (b) digitized flame front with an ellipse at the tip, (c) the radius of the flame tip curvature (R), (d) the pathlines of the seed particles.