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Attachment structure of a non-premixed laminar methane flame

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Abstract

The stoichiometry and the flame structure of the leading edge, an anchor point, of a non-premixed methane flame were investigated. Local equivalence ratio at an anchor point was measured using local chemiluminescence spectra with a high spatial resolution of 17 × 450 μm. Spatially and spectrally resolved chemiluminescence measurements were carried out along the centerline and radius of the non-premixed laminar flame. The chemiluminescence spectra measured at the flame tip contained very strong luminous spectra, while these continuous background spectra disappeared at the blue flame tip region. The chemiluminescence spectra below the blue flame region were very similar to those measured in laminar premixed methane/air flames. Based on these results, the local equivalence ratio near the anchor point was calculated. Therefore, we measure the anchor point location, its shape, and stoichiometry using the flame spectra. At the anchor point, there was an island of lower equivalence ratio of 0.65, which can be estimated as the lower flammable limit of premixed laminar flame. The size of the anchor point was of horizontal elliptical shape less than 0.6 and 0.4 mm in vertical length, which located at 1.2 mm above the burner rim and inside of the rim.

Keywords: Edge flame; Anchor point; Non-premixed flame; Local chemiluminescence measurement; Local equivalence ratio

1. Introduction

Many experimental and theoretical studies have examined the mechanism of flame stabilization and the flame structure at the leading edge of non-premixed flames [1–16]. The leading edge of a non-premixed flame is called a triple flame or a tribrachial flame [17] because three different types of flames are found along the stoichiometric contour [18]. Due to the existence of these three types of flames, a triple point is located along the stoichiometric contour. Several parameters aid in understanding this triple flame and the stabilization mechanism; these include the Lewis number effect [19], mixture fraction gradient [3], propagation speed [20,21], strain rate [22,23], heat release [24], and Schmidt number [17]. Although many numerical studies have examined this subject, very few experimental studies have been performed to demonstrate local stoichiometry. Ko et al. [7] measured the equivalence ratio at the leading edge of a tribrachial flame using Raman scattering. It is necessary to obtain a more detailed stoichiometry of the leading edge near the

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burner rim. Takagi et al. [25] investigated a detailed diffusion edge flame structure including the effect of strain rate. Takahashi et al. [26] demonstrated numerical results of a detailed flame structure of the stabilizing region of laminar diffusion flames. Furthermore, Takahashi et al. [27] demonstrated the lift flame structure and local equivalence ratio contour in numerical simulation. It is necessary to have experimental results to understand the flame holding mechanism near the burner rim, that is, an anchor point, which should related to heat loss and environmental conditions [28]. Kim et al. [29] demonstrated numerical results of the oscillating lifted flame and its flame stabilization characteristics.

The mechanism of flame stabilization is closely associated with leading edge stoichiometry and flame structure. At the leading edge of a non-premixed flame, there is a clear blue flame region. We are interested in determining whether this region is a premixed region. If we can assume that the mixing condition and stoichiometry of the leading edge of a non-premixed flame can be regarded as a premixed flame, then we can measure the stoichiometry contour, which is associated with the local equivalence ratio, based on detailed flame spectra using the local chemiluminescence intensity ratio to understand the stabilization mechanism and flame structure at the anchor point.

Chemiluminescence measurements and numerical studies have been performed, and their usefulness has been demonstrated [30] in a laminar diffusion flame. Chemiluminescence measurements at the leading edge of a non-premixed flame require a high spatial resolution.

This study investigated the local stoichiometry at the edge of a non-premixed flame and flame structure at the anchor point using local chemiluminescence and its correlation to the local equivalence ratio. To understand the mechanism of flame stabilization and the structure of the leading edge of a flame, spatially and spectrally resolved local chemiluminescence was measured. The developed Cassegrain optics [31] can collect chemiluminescence from a very small point ($17 \times 450\ \mu m$) in space. Local chemiluminescence measurements using Cassegrain optics [32,33] were made in a laminar premixed methane/air flame, and the results indicated that the ratios of OH^*/CH^*, C_2^*/OH^*, and C_2^*/CH^* are indicators of the local equivalence ratio at the laminar premixed flame front [32,33]. Moreover, local chemiluminescence measurement has been used to understand the local flame front structure in a premixed turbulent flame [34,35]. This method can be used to measure detailed spectra of local chemiluminescence and the ratios to identify the stoichiometry at the leading edge of a laminar non-premixed methane flame.

This study measured spatially and spectrally resolved chemiluminescence spectra at the leading edge of a non-premixed methane flame and demonstrated the stabilization mechanism and flame front structure.

2. Experimental set-up

A cylindrical Bunsen burner ($d = 10$ mm) [32] was used to provide a laminar methane diffusion flame. The methane flow rate was $0.5 \times 10^{-3}\ cm^3/s$, and the velocity was 6.4 cm/s. Figure 1 is a direct picture of the diffusion flame and the CH^* image measured at the leading edge with a CCD camera (CH^* filter: 431.4 nm ± 1.5 nm, transmitting efficiency 40%). As shown in Fig. 1, the leading edge of the diffusion flame was about 1.5 mm from the burner exit, that is $r = 6.2$ mm, $x = 1.5$ mm. This CH^* image is an optical path integration, not an image in a plane such as LIF [36,37], so in general it would be better to apply an Abel recombination [38]. However, in this case we did not apply Abel recombination because we needed only the location in the image.

The local chemiluminescence measurement system [31–35] is shown in Fig. 2. Cassegrain optics was used to collect local flame emissions at the flame front. The optics consisted of an optical UV-grade fiber (core diameter = 200 μm, NA = 0.2) and a pair of optimized mirrors: one concave ($d = 150$ mm) and one convex ($d = 50$ mm). The Cassegrain optics provided a high spatial resolution by minimizing the spherical aberration of the pair of mirrors and avoiding chromatic aberration. The theoretical spatial resolution of the optics was estimated using ray tracing. The effective control volume was defined using the measured relative intensity rate with a threshold level of e^{-2} times the peak value. The control volume was estimated to be 17 μm in diameter and 450 μm long, which was sufficient to detect spatially resolved flame emissions in the flame front. The collected flame emissions were guided to a grating monochromator (ORIEL: MS257) through the optical fiber. A CCD detector coupled to an image intensifier (ANDOR: DH520, gratings: 300 lines/mm) was used in the monochromator. The wavelength resolution of the grating was 0.22 nm. The gain of the image intensifier was maintained at a constant value for each measurement. The exposure time of the CCD detector was 0.2 ms. This system was the same as that used in the previous high pressure laminar flame experiment [33].

Local flame emissions from excited species received by the Cassegrain optics were also transmitted to a band-pass filtered (BPF) spectroscopy unit and photo-multipliers (PMT). The analog output signals of the PMTs were amplified, filtered, and digitized using a multi-channel A/D converter at a sampling rate of 200 kHz. Four color-splitters (interference and dichroic filters) for OH^*, CH^*,