Quantitative measurements of $CH^*$ concentration in normal gravity and microgravity coflow laminar diffusion flames

D. Giassi$^1$, S. Cao$^1$, D. P. Stocker$^2$, F. Takahashi$^3$, B. A. Bennett$^1$, M. D. Smooke$^1$, M. B. Long$^1$

$^1$Department of Mechanical Engineering and Materials Science, Yale University
$^2$NASA Glenn Research Center
$^3$National Center for Space Exploration Research

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With the conclusion of the SLICE campaign aboard the ISS in 2012, a large amount of data was made available for the analysis of the effect of microgravity on laminar coflow diffusion flames. Previous work focused on the study of sooty flames in microgravity as well as the ability of numerical models to predict its formation in a simplified buoyancy-free environment. The current work shifts the investigation to soot-free flames, putting an emphasis on the chemiluminescence emission from electronically excited $CH$ ($CH^*$). This radical species is of significant interest in combustion studies: it has been shown that the $CH^*$ spatial distribution is indicative of the flame front position and, given the relatively simple diagnostic involved with its measurement, several works have been done trying to understand the ability of $CH^*$ chemiluminescence to predict the total and local flame heat release rate. In this work, a subset of the SLICE nitrogen-diluted methane flames has been considered, and the effect of fuel and coflow velocity on $CH^*$ concentration is discussed and compared with both normal gravity results and numerical simulations. Experimentally, the spectral characterization of the DSLR color camera used to acquire the flame images allowed the signal collected by the blue channel to be considered representative of the $CH^*$ emission centered around 431 nm. Due to the axisymmetric flame structure, an Abel deconvolution of the line-of-sight chemiluminescence was used to obtain the radial intensity profile and, thanks to an absolute light intensity calibration, a quantification of the $CH^*$ concentration was possible. Results show that, in microgravity, the maximum flame $CH^*$ concentration increases with the coflow velocity, but it is weakly dependent on the fuel velocity; normal gravity flames, if not lifted, tend to follow the same trend, albeit with different peak concentrations. Comparisons with numerical simulations display reasonably good agreement between measured and computed flame lengths and radii, and it is shown that the integrated $CH^*$ emission scales proportionally to the computed total heat release rate; the two-dimensional $CH^*$ spatial distribution, however, does not appear to be a good marker for the local heat release rate.

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Introduction and Motivation

Due to the lack of buoyancy effects, microgravity flame experiments have several advantages over their normal gravity counterparts:

- The simplified flow field provides easier test cases to refine computational models.
- Microgravity allows the creation of flame structures that do not exist on Earth and enables study near free-mixing conditions. In this work, we extend the microgravity investigation from the characteristic of sooty flames (1) to the quantification of the \( CH^* \) radical in non-sooty nitrogen-diluted coflow diffusion flames. \( CH^* \) is the most abundant species for most of the blue light appearance of flames (like the diffusion flame shown in Fig. 1), and it is recognized as an important marker for both flame structure and heat release rate.

SPECTRAL CONSIDERATIONS

- The spectral contributions of molecules and species other than \( CH^* \) can be quantitatively assessed.
- The collection optics, the smaller the lens to collect light, the smaller the lens to collect light from emitting species other than \( CH^* \).

- The collected \( CH^* \) emission signal \( S_{CH^*} \) can be related to the number density \( n^* \) according to Eq. (1.2):

\[ \frac{S_{CH^*}}{A_{CH^*}} \propto \frac{1}{\lambda_{CH^*}} \frac{1}{K} \]

CH* Concentration Diagnostics

- The collected \( CH^* \) emission signal \( S_{CH^*} \) can be related to the number density \( n^* \) according to Eq. (1.2):

\[ \frac{S_{CH^*}}{A_{CH^*}} \propto \frac{1}{\lambda_{CH^*}} \frac{1}{K} \]

- The soot luminosity \( L_{soot} \) can be determined using a heated 100 \( \mu \)m S/C fiber; the fiber-emitted radiation is collimated by a lens, and thanks to the known fiber emissivity, its temperature was evaluated using color ratio pyrometry (3). The ratio between the measured fiber signal and the calculated fiber intensity (as collected by the blue channel at the self-measured temperature \( T \)) is provided a value for the intensity calibration, as in Eq. 2.

\[ \frac{L_{soot}}{A_{soot}} \propto \frac{1}{\lambda_{soot}} \frac{1}{K} \]

- The constant \( C \) is the contribution of emitting species other than \( CH^* \), while the term \( \tau \) is the transmitted energy of a photon in the blue channel, as in Eq. 3.

\[ \tau_{540} = \int_{530}^{550} S_{CH^*} d\lambda \]

Results

- The procedure to compute the \( CH^* \) concentration was initially tested on the simulated turbulent methane flame (for which previous concentration measurements are available (4)), and it displayed good quantitative agreement. The mole fraction value shown in Fig. 8 was obtained from the number density, assuming a temperature of 1500 K.

- The uncertainty in the determination of the \( S/C \) fiber temperature (130 K) can translate into a maximum uncertainty in the \( CH^* \) concentration of roughly 40%.

- Figure 9 shows the absolute \( CH^* \) concentration spatial distribution for the flames of Case A: the fuel flow is in the left half, \( CH^* \) is in the right half. The left half of each image displays the microgravity result, while the right half shows the normal gravity one. The peak \( CH^* \) concentration of both normal gravity and microgravity flames (Fig. 9) results to be weakly dependent and relatively insensitive to the fuel velocity.

Conclusions

- Quantitative measurements of \( CH^* \) concentration have been performed on selected microgravity and normal gravity SLICE flames.
- The spectral characterization of the SLICE color camera allowed the blue channel signal to be considered representative of the \( CH^* \) emission around 431 nm.
- A reference diffusion flame was spatially analyzed to investigate the contribution of chemiluminescent species other than \( CH^* \), and used to verify the validity of the proposed approach.
- The measured peak \( CH^* \) concentration displayed a higher sensitivity to coflow variations than to fuel flow variations, generally higher in normal gravity.
- It was shown that, for laminar coflow diffusion flames, the integrated radial absolute \( CH^* \) concentration scales proportionally to the simulated integrated flame heat release rate.
- The \( CH^* \) and heat release rate agreements vary reasonably well, but the variations in spatial intensities and gradients do not match.