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

D. Giassi1, S. Cao1, D. P. Stocker2, F. Takahashi3, B. A. Bennett1, M. D. Smooke1, M. B. Long1

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 tests to refine computational models.
- Microgravity allows the creation of flame conditions that do not exist on Earth and enables study near flames.

In this work, we extend the microgravity investigation from the characterisation of sooty flames [1] to the quantification of the CH* radical in non-sooty nitrogen-diluted coflow diffusion flames. CH* is responsible for most of the blue 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.

SLICE (Structure and Liftoff in Combustion Experiments)

- SLICE was an experimental campaign conducted on the International Space Station in 2012.
- One of the objectives was the investigation of the influence of microgravity on the structure of coflow laminar diffusion flames.

DSLR Camera Characterization

- Conventional chemiluminescence measures rely on an interference filter to isolate and collect the light emitted by a specific radical species.
- The spectral characteristics of the color camera allowed the signal collected by the blue channel to be considered representative of the CH* emission of the A(2Δ)/X(2Π) transition centered around 431 nm.
- Preliminary measurements, performed on a well-characterized nitrogen-diluted 65% methane reference flame, showed good chemiluminescence signal within the spectral range of relevant chemiluminescence species from the nitrogen blue channel and a 430 nm interference filter (Fig. 3-5).
- Figure 3-5 shows the normalized transmittance of a Nikon D300 SLR camera (see Fig. 1-center), calibrated and spectrally characterized to perform quantitative measurements (quantum efficiency, saturation volume fraction measurements, and CH* concentration).

CH* Concentration Diagnostics

- The collected CH* emission signal $S_{CH*}$ can be related to the number density $N$ according to Eq. (1):

$$S_{CH*} = A_{CH*} N_{CH*}/K$$

- In the SLICE setup, the calibration constant K was determined using a heated 100 μm S/C fiber; the fiber-emitted radiation was imaged through the camera, and the signal 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) provided a value for the intensity calibration, as in Eq. 2.

$$\frac{S_{Fiber}}{S_{CH*}} = \frac{A_{Fiber} N_{Fiber}/K}{A_{CH*} N_{CH*}/K}$$

- The constant C represents the contribution of emission species other than CH*, while the term $S_{Fiber}$ is the transmitted energy of a photon in the blue channel, as in Eq. 3.

$$C = \frac{S_{Fiber}}{S_{CH*}}$$

Results

- The procedure to compute the CH* concentration was initially tested on the coflow diffusion flame (for which previous concentration measurements are available [4]), and it displayed good quantitative agreement with the mole fraction value shown in Fig. 8. It was obtained from the number density, assuming a temperature of 1050 K.
- The uncertainty in the determination of the S/C fiber temperature (±30 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 front of the coflow and the flame is maintained constant. 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-right) is seen 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 characteristics 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 spectrally 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 velocity 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 variation of CH* and heat release rate distributions agrees reasonably well, but variations in spatial intensities and gradients do not match.