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

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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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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.

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 conditions that do not exist on Earth and enables study near-Rocket conditions.

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

- For the accuracy of the quantitative measurement, it is essential that the collected chemiluminescence is related to the radial space. The ratio of CH* to CO2 concentration on the collected flame signal was evaluated following a spectral characterization of the diffuse NOC methane flame. Figure 5a shows the flame spectrum collected at 7.5 mm above the burner, the horizontal and vertical axes identify the radial and spectral coordinates, respectively. The white lines demarcate the FWHM spectral width of a 430 nm interference filter, while the Nikon blue filter covers the entire range.

- Figure 5b shows the normalized radial profile of the flame chemiluminescence. The curves are obtained by spectrally integrating over the characteristic spectral regions of Fig. 5a. The integration over the entire spectral range, due to the CH* and CO2 contribution, yields a broader radial profile and explains the halo seen in Fig. 3-left.

- The radial peaks of CH* and CO2 are not coincident, when the two species are spectrally integrated, as is the case for the blue channel acquisition, the radial distance of the peak CH* from the centerline is expected to be underestimated. In the current work, however, the system magnification was such that the effect was negligible.

- The additional light emitted by CH* and CO2 will increase the recorded counts. If not corrected, this would result in overestimation of the actual CH* signal. A comparison between the chemiluminescence collected by the blue channel and a 430 nm interference filter showed that the detected signal in the blue channel, regardless of the axial position, is greater by a nearly constant factor of ~3.3, as shown in Fig. 6. (The 430 nm filter signal has been corrected to account for the partial transmissivity of the filter.)

- In cases where the conditions are such that the flame becomes partially sooty (see Fig. 7a), the blue channel will detect signal from soot, which is well-corrected, causing additional corruption of the real CH* signal. The normalized blue channel shown in Fig. 7b, the wing signal can be associated with the CH* emission, while the tip is mainly due to soot luminosity.

- A method to account for soot luminosity relies on the use of additional information that can be obtained from the camera’s green channel (Fig. 7c). Green and blue signals are normalized with respect to their maxima along the wings; since no soot is present along the two, the normalized images are subtracted to obtain one that shows the best contribution on the tip (Fig. 7d). The resulting image is then scaled to match the tip peak intensity of the blue channel, and subtracted from the original blue signal to obtain a ‘soot-free’ blue image (Fig. 7e).

SLICE Camera Characterization

- Conventional chemiluminescence measurements rely on an interference filter to isolate and collect the light emitted by a specific radical species.
- The spectral characteristics of the color camera allow the signal collected by the blue channel to be considered representative of the CH* emission of the A1Δ→X1Σ+ transition centered around 431 nm.

- Preliminary measurements, performed on a well characterized nitrogen-diluted 65% methane reference flame, showed good response to the relevant chemiluminescence profiles obtained from the Nikon blue channel and a 430 nm interference filter (Fig. 3-left).

- Figure 3-right shows the normalized transmissivities of a Nikon DFA blue filter and a 430 nm interference filter, when compared to the spectral location of relevant chemiluminescent species: the broadband blue filter is expected to collect light from emitting species other than CH*, such as *C and CO2.

- CH* Concentration Diagnostics

  - The collected CH* emission signal SCH* can be related to the number density NCH* according to Eq. (1):

    \[ S_{CH^*} = A_{CH^*} N_{CH^*} \frac{1}{ \lambda} \]

    In the SLICE setup, the calibration constant K was determined using a heated 100 μm SiC fiber; the fiber-emitted radiation was imaged by the camera, 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) provided a value for the intensity calibration, as in Eq. 2:

    \[ K = \frac{I_{Fiber(Blue)} - I_{Fiber(Blue)} \lambda} {I_{Fiber(Blue)}} \]

    - The constant C considered the contribution of emitting species other than CH*, while the term \( T_{Fiber} \) is the transmitted energy of a photon in the blue channel, as in Eq. 3:

    \[ T_{Fiber} = \frac{1}{f} \int_{0}^{f} \frac{1}{\gamma} I(x,y) dx dy \]

    - The peak of the spectrum is located in the spectral range of the interference filter, as determined from the molecular absorption coefficient (13).

Results

- The procedure to compute the CH* concentration was initially tested using a single 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 /SFC fiber temperature (1300 K) can translate into a maximum uncertainty in the CH* concentration of roughly 40%.

- Figure 9-left shows the absolute CH* concentration spatial distribution for the flames of Case A: the fuel flow is initially at 10% of the nominal value and is then 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.

- Figure 10-left shows the absolute CH* concentration spatial distribution for the flames of Case B: the coflow is increased as the fuel nozzle is moved outward, thus maintained constant. For this configuration, the peak CH* concentration of both microgravity and normal gravity flames (Fig. 10-right) shows a dependence on the coflow velocity.

- The computational model implemented to simulate the SLICE diffusion flames is based on the NRC-Smooth-vorticity-velocity formulation of the governing equations [6], the gas chemistry is described by 42 species and 250 reactions in the GRI 3.0 mechanism [7]. The resulting coupled and nonlinear equations are solved using a modified Newton’s method with a B-GASTAB linear solver.

- Figure 11 shows the comparison between the integrated CH* absolute concentration distribution in a cross section, and the integrated computed heat release rate for Cases A and B. The correlation between the two quantities is seen to be weakly concordant, confirming that the total CH* chemiluminescence can be a useful marker for the total flame heat release rate in laminar coflow diffusion flames.

- Figure 12-left displays the comparison between the integrated CH* absolute concentration distribution and the normalized local heat release rate for a representative flame of Case A: Despite minor differences in flame structure, spatial distributions of the two quantities is similar and both follow the position of the flame front. On the other hand, gradients and intensities do not match; in Fig. 12-right the normalized radially integrated counts of CH* concentration and heat release rate are plotted as functions of the axial coordinate, demonstrating the difference between CH* and heat release rate spatial gradients.

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 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 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 improved CH* and heat release rate distributions agrees reasonably well, but the variations in spatial intensities and gradients do not match.