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Application of Soot Reabsorption Correction for Soot Laden Coflow Diffusion Flames

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Abstract
Ratio pyrometry is commonly used for high temperature measurements. It is particularly useful for measuring the temperature of soot in flames, because measurements are nonintrusive and can be performed with a standard commercial DSLR camera. However, radiation reabsorption by soot particles can lead to significant error in flames with high soot concentrations. A correction must be implemented to account for this. One approach to this correction for two-color ratio pyrometry measurements is compiled and documented by Kempena and Long [1]. The goal of this study is to create a Matlab code that implements the radiation reabsorption correction as described. The MATLAB code will be used to examine the effect of soot radiation reabsorption in coflow diffusion flames experiments conducted in the Laboratory for Advanced Combustion and ENergy Research (LACER) at Washington University in St. Louis.

Background
Two-color ratio pyrometry is used herein to measure the soot temperature and soot volume fraction in coflow diffusion flames. These flames are assumed to be axisymmetric. Because only a commercial DSLR camera is needed, this method has the dual advantages of being fast and having high spatial precision because a modern camera can rapidly take high resolution photos. The measurement technique is also non-intrusive because nothing is required to be placed inside the flame. A MATLAB script developed by Irace for calculating temperature and soot volume fraction with the average of results from all three two-color ratios from the camera (Red/Green, Green/Blue, Red/Blue) was used.

For flames with particularly high soot volumes, the impact of the reabsorption of light by the soot particles should be accounted for in calculations. Beer-Lambert’s law is utilized to estimate soot volume fractions from the temperatures calculated by pyrometry. Assumptions made about optically thin flames, uniform optical properties, and wavelength dependence break down in the cases of dense, sooty flames. Additionally, scattering due to the soot particles causes variances throughout the flame and Beer-Lambert’s law cannot reliably calculate soot volume fraction. This can be corrected for by estimating the impact of scattering with the initial estimate for soot volume fraction. With this corrective factor, iterations of calculating corrected signals, soot volume fraction, and temperature will converge to a corrected value that accounts for self-absorption.
Method
A MATLAB script [Appendix A] was developed to conduct one iteration of the self-absorption corrective process. The script requires SR, SG, SB which are the uncorrected signal values for R, G and B, respectively. The line-of-sight signal is deconvolved to a radial distribution, as the flame is axisymmetric. For the calculations, the x-y plane is defined as parallel to the burner face, with the x axis pointing towards the camera. The z axis is normal to the burner face. Additionally, the script needs the uncorrected soot volume fraction (fv) and Temperature (T). These quantities can be calculated using Irace’s script [Appendix B] which utilizes pyrometry and an absolute intensity calibration. The script also utilizes a few camera calibration constants and the camera conditions of the flame under consideration. The user must provide the resolution of the camera in millimeters/pixel and the system spectral response for each color channel (η). First, the script reconvolves the deconvolved signal, soot volume fraction, and temperature in order to reattain independence in the x and y directions. Next, for a certain color channel, the script iterates through wavelengths from 0.4 to 0.7 micrometers (the detection wavelengths). Then the script calculates the soot absorption coefficient (E) with the soot’s refractive index (n, k), found with a fit from Chang and Charalampopoulos [2]. With the soot absorption coefficient, soot volume fraction, and physical constants, the script calculates the local emission rate (BK). Integrating BK across x calculates the signal intensity incident on the detector (I). The script then calculates a second signal intensity incident (I_abs) by considering an attenuation factor. Then the script integrates both across the wavelengths previously listed, weighted by the system spectral response. Finally the script uses the ratio between the two weighted integral and multiplies by the original signal to get the corrected signal. If needed, the script’s inputs can be updated and the user can rerun the script for the next iteration of corrections.
**Results**

In order to test the code, the script is run on a few sample coflow diffusion flames. The figure below shows 9 iterations.

![Figure 1. 9 iterations of correction](image)

The selected z value for this plot was the z that contained the largest initial soot volume fraction. Note the significant correction and convergence. The initial soot volume fraction is the largest plotted value. Additionally, data from an ethylene coflow flame is tested and shown in figure 2.
The z value selected is chosen to be the location of the maximum soot volume again. Note the much faster convergence and small magnitude of change between iterations. This flame is far less soot laden than the flame in figure 1 (note the y axis values). Although these preliminary results show promise for the ability of this script to converge, further validation must be done to ensure the efficacy of the methodology and the script. This can be conducted by comparing to data obtained from a simulated flame with similar parameters.

References

Appendix
A - SootReabsorption.m
B - TwoColorSootCalcs.m