A Survey of Techniques for Optical Measurement of Flare Combustion Efficiency

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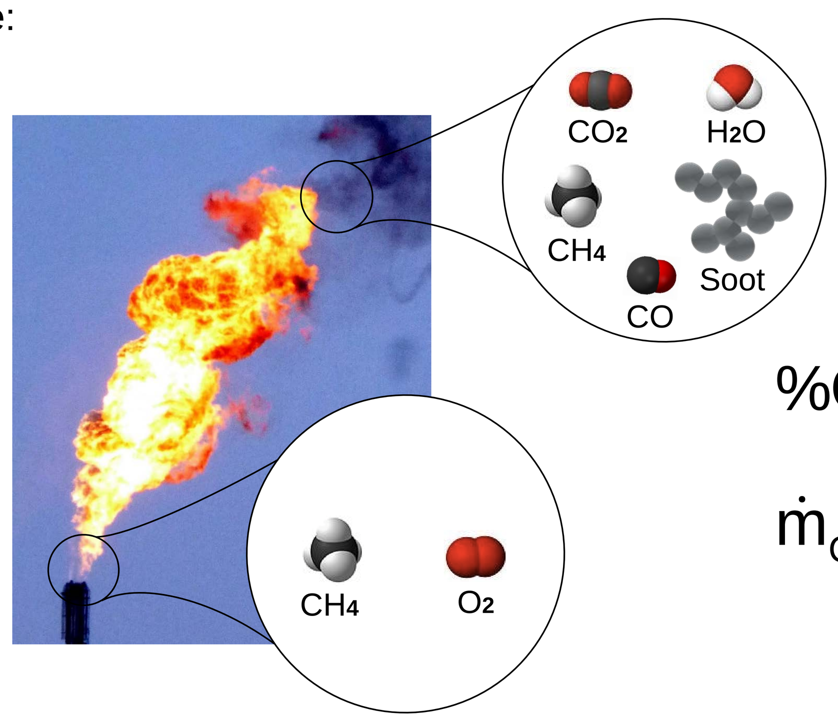
Motivation

- Methane has a global warming potential 34 times that of carbon dioxide over 100 years, by mass [1]. To mitigate the environmental impact, health hazards, and risk of explosion of methane, flaring is used to safely convert methane and other unwanted hydrocarbons.
- Combustion efficiency is used to gauge the effectiveness of flaring. It is defined as the mass of carbon affixed in carbon dioxide leaving the flare divided by the total mass of carbon in the fuel stream entering the flare:



$$\%CE = \frac{\dot{m}_{C,CO_2}}{\dot{m}_{C,fuel}},$$

$$\dot{m}_{C,fuel} = \dot{m}_{C,CO_2} + \dot{m}_{C,CO} + \dot{m}_{C,CH_{4unburned}} + \ldots$$

- Variable environmental conditions can dramatically reduce combustion efficiency, e.g. crosswind, jet velocity, and humidity
- Point measurements systematically overestimate global combustion efficiency [2]
- Recent progress in mid-infrared optics enables an optical approach to estimate the combustion efficiency

Measurement Technique

1 **Capture Image** Use an IR camera to capture radiative emission from the flare plume

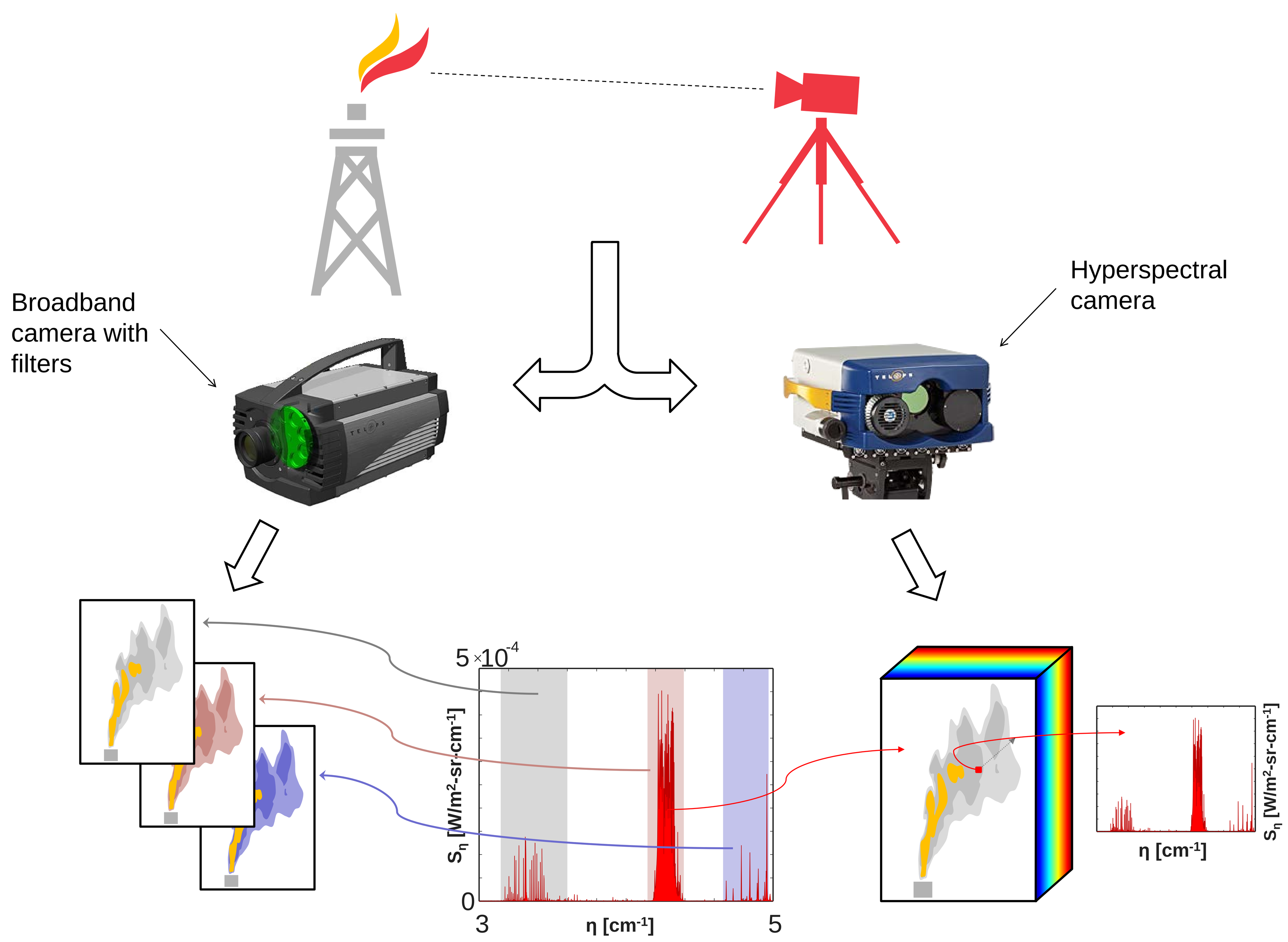
2 **Estimate the Column Density** Apply inverse analysis to estimate the amount of each gas along a line-of-sight

3 **Post-processing** Calculate the flare effectiveness in transforming fuel to carbon dioxide

1 Capture Image

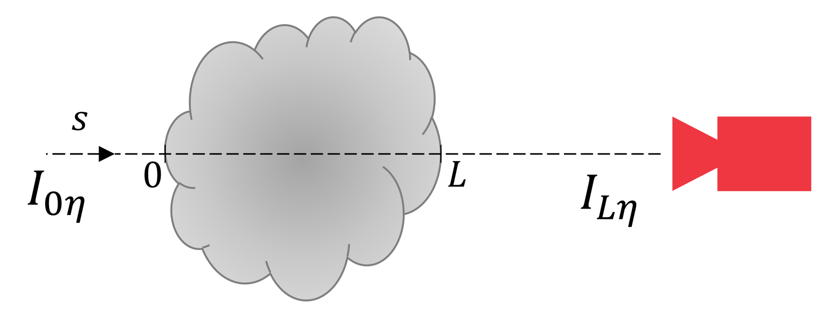
The brightness of a pixel is related to the column density of participating gases along the corresponding line-of-sight (LOS). Two options:

1. A broadband camera with filters
2. FTIR imaging spectrometer (hyperspectral camera) which gives a spectral information for each pixel.



2 Estimate the Column Density

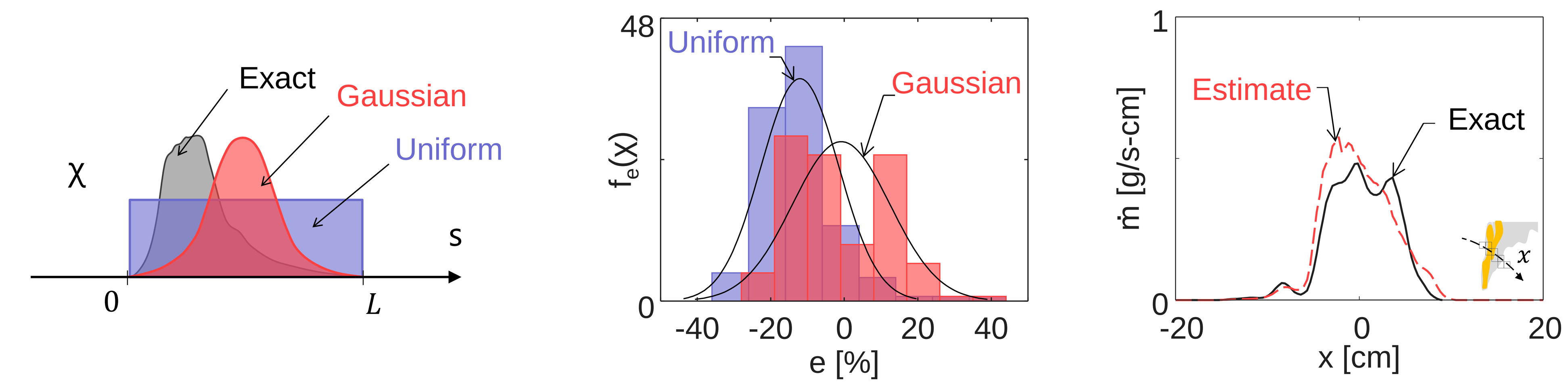
The number of molecules along a LOS is inferred from pixel brightness at multiple wavelengths/filters. This inverse problem is ill-posed, since are an infinite set of temperature and concentration profiles along the LOS that could explain the collected images. Two common assumptions are used to close this problem: (1) temperature and gas concentration are uniform over each LOS; (2) temperature and concentration follow a Gaussian distribution along each LOS.



Nonscattering RTE

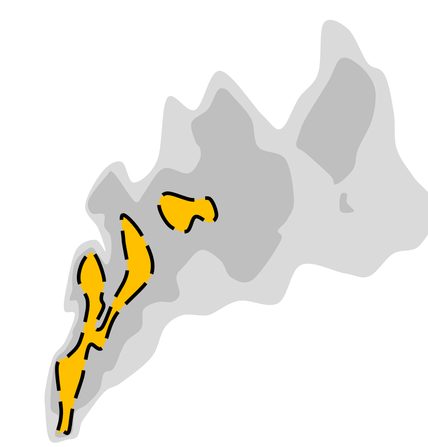
Background, Emission, Absorption, Reabsorption

$$I_{L\eta} = I_{0\eta}\exp\left\{-\int_0^L \kappa_\eta ds\right\} + \int_0^L \kappa_\eta I_{b\eta}\exp\left\{-\int_s^L \kappa_\eta ds'\right\} ds$$



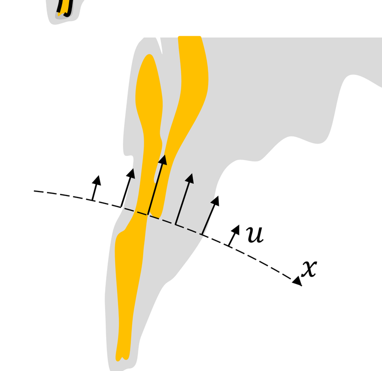
3 Post-processing

Finally, the column density is post-processed to obtain the combustion efficiency. The amount of fuel entering the flame can be estimated by summing all carbon-containing species within the plume, including CO_2. With this information it is possible to calculate the global efficiency by two methods:



Average efficiency in the flame envelop

This approach uses brightness difference between the flame and background to determine the flame envelope. Global efficiency is defined as the mean combustion efficiency of each pixel within the envelope. This approach does not weigh the global efficiency with respect to gas velocity. Other possible sources of error include the radiative emission from soot that is present in this region.

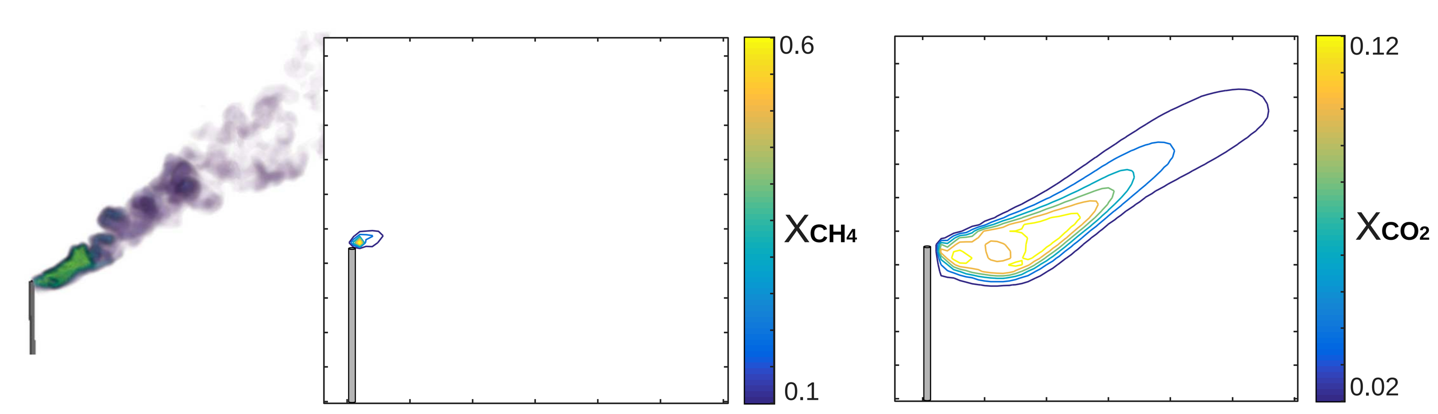


Control surface method

A control surface (arc) is defined that transects the plume. The mass-weighted velocity is computed by applying image correlation velocimetry (ICV) to successive images. By coupling the velocity and column density of each pixel along the arc it is possible to estimate the mass flow of each component that crosses the surface. The combustion efficiency is estimated by the mass flow of carbon fixed to carbon dioxide over the carbon mass flow of all combustion products. It is possible to track the combustion efficiency progress over the flare by defining several control surfaces.

Large-eddy simulation

The experiment will be prototyped using an LES simulation [3]. Simulated infrared or hyperspectral images will be used to generate estimated column densities and combustion efficiencies, which will be compared with ground-truth values



Conclusions and Future Work

- Optical gas imaging is emerging as a technique to calculate flare efficiency through standoff measurements
- The technique requires assumptions about the distribution of temperature and species concentration along a line-of-sight. Gaussian distributions are the most accurate.
- The experiment will be prototyped using a large-eddy simulation to identify the best instrumentation, measurement protocol, and data processing techniques

References

[1] T. Stocker, *Climate change 2013: the physical science basis: Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, 2014.
[2] J. H. Pohl, B. A. Tichenor, J. Lee, and R. Payne, "Combustion Efficiency of Flares," *Combustion Science and Technology*, vol. 50, no. 4-6, pp. 217–231, 1986.
[3] A. Jatale, P. J. Smith, J. N. Thornock, S. T. Smith, and M. Hradisky, "A Validation of Flare Combustion Efficiency Predictions From Large Eddy Simulations," Journal of Verification, Validation and Uncertainty Quantification, vol. 1, no. 2, p. 021001, Oct. 2015.

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