Gas Mixture Quantification using Optical Gas Imaging

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Abstract

- Mid-wavelength infrared (MWIR) imaging can quantify the column density of a single species at a known temperature. Applications involving gas mixtures or unknown gas temperatures, e.g. flare combustion efficiency (CE), require simultaneous images captured at multiple distinct wavelengths or over multiple spectral bands.
- Imaging Fourier transform spectrometers (IFTS) generate a hypercube of two-dimensional images evaluated at thousands of individual wavelengths. An IFTS contains a beamsplitter and a pair of mirrors, one of which is moving, resulting in a sequence of broadband images over slightly different optical path lengths. Superimposing these images produces constructive and destructive interference patterns (interferogram), which is Fourier transformed into a spectrum.
- Gas temperature and column density of individual species along a line-of-sight can be inferred from a spectroscopic model. This information is combined with velocity field estimates computed from a sequence of images using an optical flow diagram to obtain mass fluxes.
- Two experiments were used to evaluate the capability of the IFTS (Telops Hyper-Cam MW) for assessing flare combustion efficiency:
  1. A heated vent of CO_2/CH_4
  2. A laboratory-scale air-assisted flare
- In both cases a defined background represents sky temperature, and the flow rates and concentrations are measured independently.
- The IFTS accurately determined CO_2 and CH_4 mass fluxes from the heated vent apparatus, highlighting its capability for quantifying fugitive emissions of multicomponent gases.
- For the flare, the technique accurately measures the CH_4 mass flux but significantly over-predicts the CO_2 mass flux and consequently over-predicts the CE.
- Issues with the CO_2 measurement are attributed to turbulence-induced scene change artifacts (SCAs). Due to turbulence the gas concentration and temperature fluctuate as the interferogram is being assembled. These fluctuations superimpose on the interference patterns, leading to errors in the transformed spectrum. The hypothesis was tested simulating contaminated interferograms with different gas concentrations and temperatures. Results were compared with SCAs found in IFTS data collected from the laboratory flare.
- Future work is focused on developing measurement procedures and data analysis techniques that mitigate the impact of SCAs on flare CE measurements with the IFTS.

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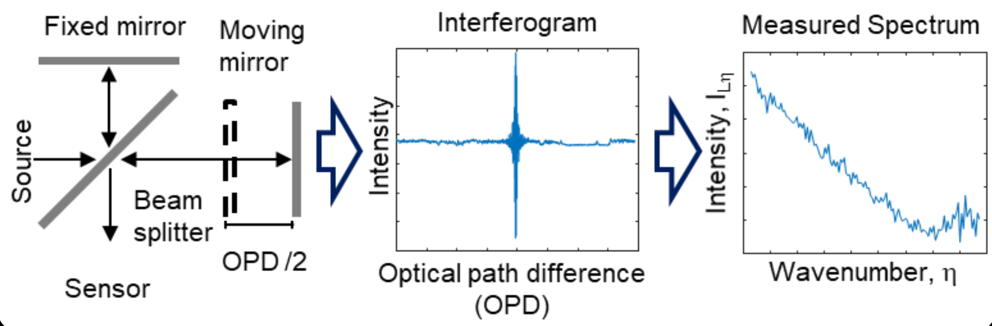
1 Motivation

- The Canadian oil and gas industry needs to quantify gaseous emissions in various scenarios, e.g. reporting fugitive emissions and assessing flare combustion efficiency.
- Optical gas imaging using mid-wavelength infrared (MWIR) cameras provides two-dimensional representations of gas concentration.
- Many gas releases consist of mixtures, or gases at an unknown temperature, which require simultaneous measurements at multiple wavelengths. These can be generated using an imaging Fourier transform spectrometer (IFTS).

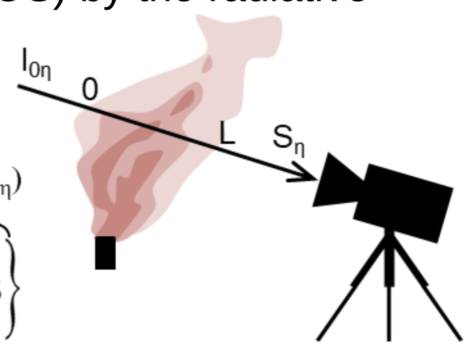
2 Imaging Fourier-transform spectrometer (IFTS)

The IFTS generates two-dimensional interferograms, which are Fourier transformed into a hypercube of spectrally-resolved images.



3 Measurement model

The spectral intensity S_η incident in each pixel is related to the gas concentration and temperature along the line-of-sight (LOS) by the radiative transfer equation (RTE).

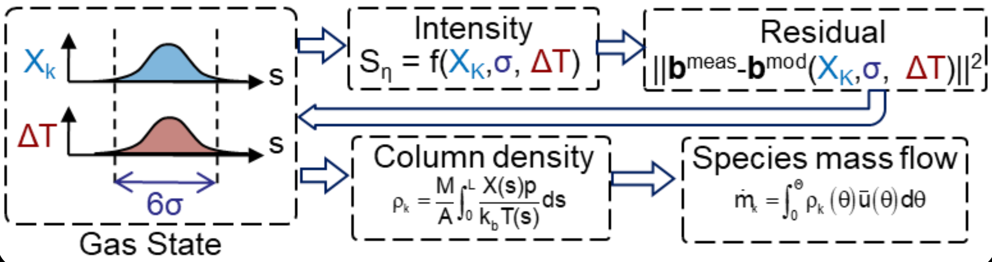


$$S_\eta = I_{0\eta}\exp\left\{-\int_0^L \kappa_\eta(s)\,ds\right\} + \int_0^L \kappa_\eta(s) I_{b\eta}(s) \exp\left\{-\int_s^L \kappa_\eta(s)\,ds'\right\} ds$$

Background; Transmittance $(1-\alpha_\eta)$; Absorption coefficient; Blackbody emission; Re-absorption

4 Spectroscopic model

- IFTS data can be used to infer temperature and species column densities simultaneously.
- The background intensity, $I_{0\eta}$, is obtained from pixels that do not contain target species.
- Species molar fraction and temperature are parametrized as Gaussian profiles along the LOS, and the species absorption coefficient is simulated using the HITRAN database.

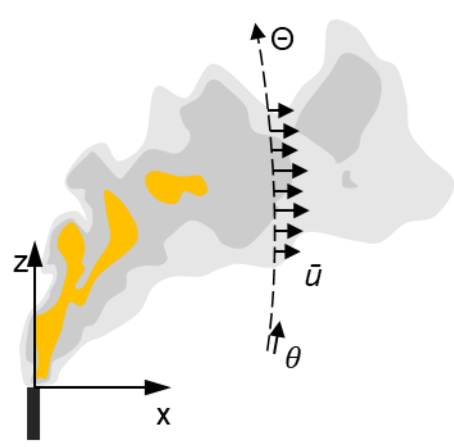


5 Flare combustion efficiency

- CE is the ratio of the mass of carbon affixed to CO_2 to the total mass of carbon in the fuel stream. Flare CE may be impacted by cross-winds (fuel stripping) and steam-assist.

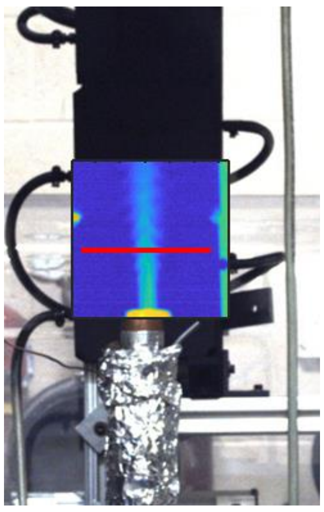
$$CE \approx \frac{\dot{m}_{C,CO_2}}{\dot{m}_{C,CO_2} + \dot{m}_{C,CH_4}}$$

- The mass flow on a control surface is given by the pixel's column densities, and intensity weighted velocities.



6 Experiments

- To simulate the combustion products of a 50% efficient flare, a 1/1 mixture of CO_2/CH_4 was released at a 10 SLPM rate and heated.
- A second experiment was carried out on laboratory-scale air-assist flare with 5 SLPM of CH_4 and 120 SLPM of air
- In both cases the gas was released in front of a cooled black background that represented a cloudy sky



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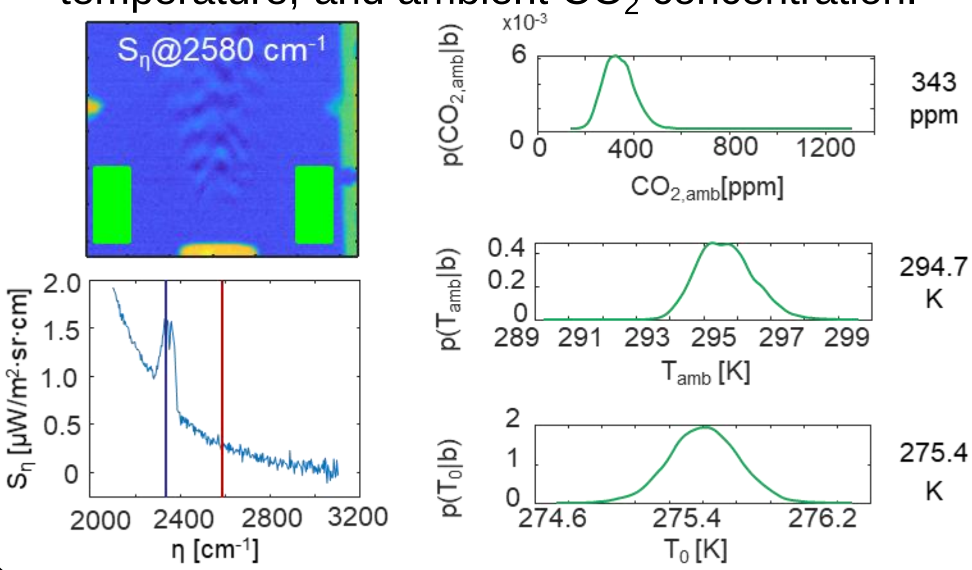
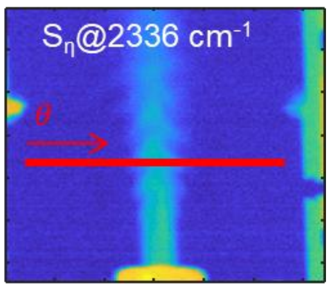
Background measurement (7)

- Pixels outside the gas flow were used to measure the background emission, ambient temperature, and ambient CO_2 concentration.

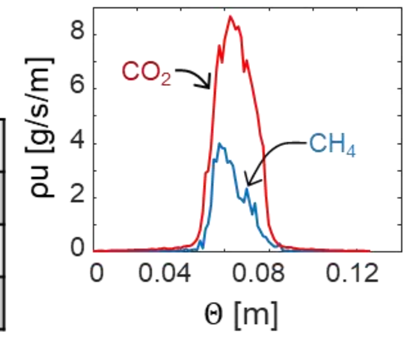


Heated vent experiment (8)

- Column densities and temperature of both species were inferred using the spectroscopic model for pixels along a control surface.
- These were combined with the velocity field found using optical flow to obtain mass flow rates.

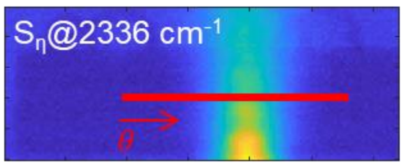


	Ground truth	IFTS
$\dot{m}_{CH4}$	0.060 g/s	0.066 g/s
$\dot{m}_{CO2}$	0.164 g/s	0.189 g/s
CE	0.500	0.513

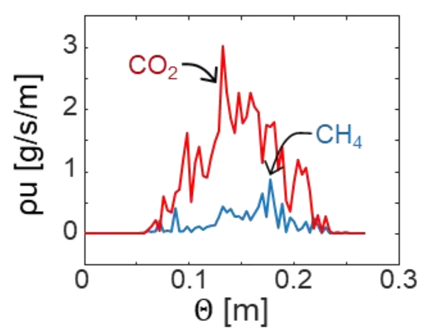


Flare efficiency measurement (9)

- The same procedure (background inference, column densities estimation, and mass flow) was used with the combustion products of the laboratory scale flare.
- Combustion products were collected and analyzed to determine ground truth CE.

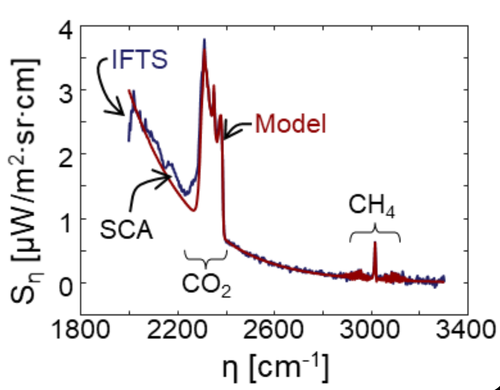


	Ground truth	IFTS
$\dot{m}_{CH4}$	0.028 g/s	0.035 g/s
$\dot{m}_{CO2}$	0.074 g/s	0.193 g/s
CE	0.50	0.67



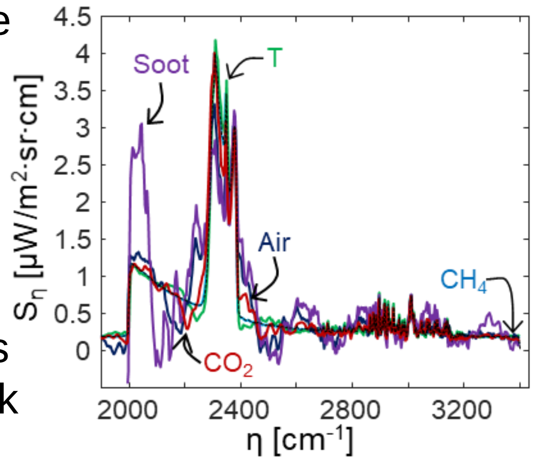
Results and discussion (10)

- The method accurately estimated the mass flow of CO_2 and CH_4 from the heated vent.
- In the flare experiment, CH_4 mass flow was accurately estimated but CO_2 mass flow was significantly over-predicted. The error is likely caused by scene change artifacts (SCAs).
- SCAs are caused by turbulence-induced intensity fluctuations that contaminate the interferogram, leading to errors in the recovered spectra.



Scene change artifacts (SCA) (11)

- Spectral data were simulated by adding pockets of CO_2, CH_4, air, and soot to the image during the interferogram acquisition.
- CO_2, air, and soot pockets strongly influence the CO_2 band wings.
- CH_4 pockets did not affected the data significantly.
- Fluctuations in gas temperature also has a comparatively weak effect.



Conclusions and future work (12)

- The IFTS can quantify species concentrations and gas temperatures simultaneously for heated vents, but flare measurements of CO_2 are affected by scene change artifacts.
- The CO_2 spectral region is more affected by turbulence-induced SCAs, leading to an over-prediction of CO_2 mass fluxes.
- Future work will focus on mitigating SCAs, e.g.
  - Discarding spectral lines most affected by SCAs in the regression procedure.
  - Making the inference over the space (OPD) domain to reduce the effects of gas changes as each point of the interferogram temporally close to each other.

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