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Assessing Flare Combustion Efficiency using Imaging Fourier Transform Spectroscopy

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A B S T R A C T

Flaring plays a critical role in reducing the environmental impact of upstream oil and gas processing by converting methane and other gaseous hydrocarbons into CO₂, which has a lower global warming potential. This process is highly efficient under ideal conditions but efficiency may be significantly lower under certain scenarios such as fuel stripping under crosswind and emission of volatile organic compounds and unburned fuels due to over-aeration or over-steaming in assisted flares. This study assesses the potential of using imaging Fourier transform spectrometers (IFTSs) to directly measure combustion efficiency by combining species column densities estimated from a spectroscopic model with intensity-weighted velocities found using an optical flow model. Simulated measurements using a computational fluid dynamics (CFD)-large eddy simulation of a flare in a crosswind are used to establish the technique’s viability, followed by experimental measurements on a heated gas vent to validate the optical flow model. Finally, preliminary measurements are carried out on a laboratory-scale steam and air-assisted flare. While the simulated measurements and heated vent experiments support the feasibility of this approach, experimentally-derived spectra from the lab-scale flare were contaminated with artifacts attributed to turbulent fluctuations, which complicates the quantitative interpretation of the IFTS data.

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1. Introduction

The oil and gas industry uses flaring to dispose of unwanted flammable gases safely. Approximately 3.5% of global natural gas production (143 billion m³ in 2012) cannot be stored or used locally [1] due to intermittent gas flow, low gas heating value, the presence of contaminants, or lack of infrastructure [2]. In these cases, the gas must be flared or vented directly into the atmosphere. Methane (CH₄), the main component of natural gas, has a global warming potential 36 times greater than carbon dioxide (CO₂) over 100 years for the same mass [3], so burning the fuel to produce CO₂ significantly decreases the greenhouse effect of the gas emitted.

Emissions from flaring represent about 0.5% of the global CO₂ equivalent emission (53.5 Gt in 2012 [4]), assuming that all the fuel is converted into CO₂ and excluding the impact of black carbon deposition on the environment. This estimate assumes that flares have a 98% combustion efficiency (CE), i.e., 98% of all fuel is converted to CO₂, but recent studies [5–10] suggest that some conditions can significantly reduce this conversion, e.g., due to crosswinds or excessive addition of air or steam for smoke suppression. The interaction between the crosswind and the flare stack leads to an aerodynamic mechanism that diverts unburned fuel from the flare combustion zone [5], the extent of which depends on the wind speed relative to the fuel velocity [11]. Injecting air or steam into the flare stream near the flare stack exit can improve fuel/air mixing, thereby reducing soot formation [12]. However, excessive air or steam injection disrupts the combustion process and, in extreme cases, can lead to flame extinction [13, 14].

Concerns about the impact of flaring on climate change, particularly when considering non-ideal flaring conditions, present a need for reliable techniques to quantify flare CE. Recent advancements in mid-infrared optoelectronics, particularly the development of imaging Fourier transform spectrometer (IFTS), make stand-off measurements of flare CE theoretically possible. These instruments combine the spectral resolution of a spectrometer and the spatial resolution of an IR camera to provide 2D hyperspectral images of a scene. In the context of quantifying gas emissions, many IFTSs have sufficient spectral resolution to “fingerprint” gaseous species from absorption and emission lines. At the same time, the 2D imaging feature can be used to map gas species
concentrations and is particularly useful in scenarios where gas species are non-uniformly distributed within a plume. IFTSs have been used to quantify gaseous emissions from smokestacks and other sources. Gross et al., for example, successfully measured the mass flow of Multiple species from a smokestack using the sky as background [15]. Furthermore, it is possible to use the IFTS to measure the CH\(_4\) emission from natural sources with complex backgrounds [16] and to study turbulent combustion from gas turbines [17] and jet flames [18], among other related applications [19]. There also exists a commercial IFTS-based product for quantifying flare CE [20], although its effectiveness has yet to be conclusively demonstrated in the open literature.

Calculating flare CE requires quantifying the mass flow rates of CO\(_2\) and unburned fuel within the flare plume. The quantification is done in two steps: first, column densities of the radiatively-participating species, as well as the temperature, are inferred by inverting a spectroscopic model derived from the radiative transfer equation. Second, CO\(_2\) and CH\(_4\) column densities are combined with velocities to obtain mass flow rates, which are used to calculate the CE. This paper begins by presenting the measurement model that relates the plume concentration and velocity to the IFTS images. The theoretical viability of this approach is then established by inverting synthetic IFTS data generated using a computational fluid dynamics-large eddy simulation (CFD-LES) of a flare in a crosswind. Next, the measurement model is verified by recovering mass flow rates of CH\(_4\) and CO\(_2\) mixtures from a heated vent apparatus. Finally, preliminary measurements are presented on a laboratory-scale steam- and air-assisted flare. These results show that, while this technique is theoretically viable and can accurately infer CH\(_4\) and CO\(_2\) mass flow rates from the heated vent, in the case of the lab-scale flare, artifacts in the measurement spectrum preclude accurate estimates of the flare CE.

2. Measurement model

Calculating flare CE requires knowledge of both the species column densities and the intensity-weighted velocity of these species within the flare plume.

2.1. Flare combustion efficiency

The overall flare CE is defined as the fraction of the fuel’s carbon content that is converted to CO\(_2\).

\[
\text{CE} = \frac{\dot{m}_{C,\text{CO}_2}}{\sum \dot{m}_{C,\text{fuel}}} \quad (1)
\]

The mass flow rate of fuel entering the flare is not often known. Instead, it is inferred from a mass balance on the gas-phase carbon-containing species in the flare plume, which arise from incomplete combustion of a hydrocarbon

\[
\text{C}_x\text{H}_y + \alpha \text{O}_2 = b \text{CO}_2 + c \text{H}_2\text{O} + d \text{CO} + e \text{CH}_4 + f \text{C}_\text{soot} + \sum_{i,j} h_{ij} \text{CH}_j \quad (2)
\]

In most upstream oil and gas flares, the fuel mainly consists of CH\(_4\) [21, 22]; trace amounts of reformed gas-phase hydrocarbons, C\(_i\)H\(_j\), produced by the incomplete combustion are not meaningful in terms of the overall carbon balance and can be neglected [7, 10, 22]. Likewise, CO and soot do not significantly influence the CE measurements [22, 23]. Hence CO\(_2\) and unburned fuel, almost exclusively CH\(_4\), are the two key parameters that affect the CE calculation,

\[
\text{CE} = \frac{\dot{m}_{C,\text{CO}_2}}{\dot{m}_{C,\text{CO}_2} + \dot{m}_{C,\text{CH}_4} + \dot{m}_{C,\text{CO}} + \dot{m}_{C,\text{soot}}} \approx \frac{\dot{m}_{C,\text{CO}_2}}{\dot{m}_{C,\text{CO}_2} + \dot{m}_{C,\text{CH}_4}} \quad (3)
\]

The mass flow rates of these species are calculated using a control surface aligned perpendicular to the camera image, as shown in Fig. 1. The control surface corresponds to a row of pixels in the 2D image; the pixel column density for each species is derived from the ideal gas law

\[
\rho_k = \frac{M_k N_k}{A} = \frac{M_k}{A} \int_0^1 \chi_k(s) p \rho_k(s) \, ds \quad (4)
\]

where \(A\) is Avogadro’s number, \(N_k\) is the column number density of the \(k\)th species, \(p\) is the pressure (assumed to be 1 atm), \(\chi\) is the species mole fraction along the line-of-sight (LOS), \(T\) is the temperature along the LOS, and \(k_b\) is Boltzmann’s constant. The carbon mass flow rate can be approximated by combining the column density with the gas velocity normal to the control surface

\[
\dot{m}_{C,k} = \frac{M_C}{M_k} \dot{m}_{k} = \frac{M_C}{M_k} \int_0^1 \rho_k(\theta) \dot{\bar{u}}(\theta) \, d\theta \quad (5)
\]

where \(\rho_k\) is the column density of the \(k\)th species in the LOS of the pixel located at parametric distance \(\theta\) along the control surface, \(\dot{\bar{u}}\) is the partial density-weighted normal velocity that is averaged along the pixel LOS, and \(M_C\) and \(M_k\) are the carbon molar mass and \(k\)th species molar mass, respectively.

The density-weighted velocity field projection can be calculated by analyzing successive images via an optical flow algorithm [24]. Combining Eqs. (3)-(5) results in

\[
\text{CE} \approx \frac{\frac{\int_0^1 N_{\text{CO}_2}(\theta) \dot{\bar{u}}(\theta) \, d\theta \rho_{\text{CO}_2}(\theta) \dot{\bar{u}}(\theta) \, d\theta}{\int_0^1 N_{\text{CH}_4}(\theta) \dot{\bar{u}}(\theta) \, d\theta}}}{\frac{\int_0^1 N_{\text{CO}_2}(\theta) \dot{\bar{u}}(\theta) \, d\theta}{\int_0^1 N_{\text{CH}_4}(\theta) \dot{\bar{u}}(\theta) \, d\theta}} \quad (6)
\]

In discrete form this amounts to summing over the pixels that form the control surface

\[
\text{CE} \approx \frac{\sum_{i,j} N_{\text{CO}_2,i} \bar{u}_i}{\sum_{i,j} N_{\text{CH}_4,i} \bar{u}_i + \sum_{i,j} N_{\text{CO}_2,i} \bar{u}_i} \quad (7)
\]

where the number column density of each species is inferred from the pixel brightness via the measurement model derived from the radiative transfer equation, and the velocity field is found from the optical flow algorithm.
2.2. Spectral intensity model

The incident spectral intensity that reaches each pixel is modelled by the radiative transfer equation (RTE). Each pixel corresponds to a LOS through the plume, as shown in Fig. 2.

Molecular scattering is negligible at the mid-infrared wavelengths used for this measurement. The spectral intensity incident upon the camera lens is given by

\[
l_{iL} = l_{i0} \exp \left[ - \int_0^L \kappa_{\eta, \text{mix}}(s) \, ds \right] 
+ \int_0^L \kappa_{\eta, \text{mix}}(s)I_{ob}[T(s)] \exp \left[ - \int_s^L \kappa_{\eta, \text{mix}}(s') \, ds' \right] \, ds
\]  

(8)

where \(l_{iL}\) is the spectral intensity incident on the camera aperture, \(l_{i0}\) is the background intensity, \(s\) is the distance parameter along the LOS as shown in Fig. 2, and \(I_{ob}\) is the blackbody emission at the local gas temperature, \(T(s)\). The spectral absorption coefficient of the mixture at \(s\), \(\kappa_{\eta, \text{mix}}(s)\), is the sum of the absorption coefficients for all the \(N_i\) participating species,

\[
\kappa_{\eta, \text{mix}}(s) = \sum_{k=1}^{N_i} \kappa_{\eta, k}[\chi_k(s), T(s)]
\]

(9)

which are taken to be CO\(_2\), CH\(_4\), and H\(_2\)O. These absorption coefficients, in turn, are calculated by summing over the transitions for each species

\[
\kappa_{\eta, k}(s) = \sum_{ij} S_{ij}[T(s)] f_{ij}[\eta, \eta_{ij}, T(s), p] \chi_k(s) \frac{p}{k_B T(s)}
\]

(10)

where \(S_{ij}\) is the spectral line intensity of the transition between energy states \(i\) and \(j\) for species \(k\), and \(f_{ij}[\eta, \eta_{ij}, T(s), p]\) is the Lorentz line shape function. (Collision broadening is the dominant broadening mechanism in the flare plume downstream of the combustion zone.) Line strengths and line shape parameters are taken from HITRAN [25], assuming air broadening. To reduce the computational time, a lookup table for each absorption coefficient is precomputed for each species with a spectral resolution of 0.05 cm\(^{-1}\), molar fraction resolution of 0.05, and a temperature resolution of 1 K.

2.3. Imaging Fourier-transform spectrometer (IFTS)

The spectral intensity incident on the camera aperture is further processed to reflect the instrument function of the specific IFTS, which, in this work, is a Telops Hyper-Cam MW. The instrument has a spectral range of 2000 to 3333 cm\(^{-1}\) (3 to 5 \(\mu\)m) with spectral resolution up to 0.25 cm\(^{-1}\). In this study, a resolution of 4 cm\(^{-1}\) is used. The Hyper-Cam is equipped with a 320 \(\times\) 256 pixel focal plane array coupled to a Michelson interferometer. Fig. 3 shows a schematic of the device. More information on Michelson interferometer can be found in Ref. [26]. The output of the instrument is therefore an estimation of the autocorrelation function of the field, also known as an interferogram. An inverse Fourier transform (FT) is then applied to these interferograms to produce the 3D data cube consisting of 2D images with an additional spectral dimension, called a hyperspectral cube.

The modelled spectral intensity is apodized to account for the finite maximum optical path difference (MOPD) of the interferometer, which is equivalent to truncating the higher frequencies on the FT. As noted in Ref. [27], the divergence contribution to the ILS is negligible because of the small instantaneous field of view (IFOV) of each pixel. The down-sampled data is obtained by a convolution of the incident spectral intensity and the instrument line shape (ILS) function

\[
S_{\text{IFTS}, i} = \int_0^\infty I_0 F(\eta_i - \eta) \, d\eta
\]

(11)

The IFTS data is computed for each of the interferometer’s spectral bins, which is then stored in the data vector \(b\). The instrument line shape can be modelled as a function of the MOPD, \(\eta_{\text{res}}\), following Ref. [27]. In the ideal case of a symmetric MOPD interferometer, the ILS is the FT of the boxcar function given by

\[
F(\eta) = 2\pi \eta_m \sin((2\pi \eta_m)\eta)
\]

(12)

where \(\sin(x) = \sin(x)/x\). The MOPD is related to the spectral resolution, \(\eta_{\text{res}}\), according to

\[
\eta_m = \frac{1.20671}{2 \times \eta_{\text{res}}}
\]

(13)

Although the camera coupled to the interferometer has a high frame rate, the time required to measure a single data cube is approximately the sum of the time required to record an image multiplied by the number of discrete OPDs, and far exceeds the characteristic time of turbulent artifacts in the flow field. Turbulent fluctuations that occur as the mirror transits through its OPD may cause scene change artifacts (SCAs) in the recovered intensity spectrum. The influence of SCAs are mitigated by reducing the time required to acquire each frame by reducing the spatial resolution, reducing the number of frames within each hyperspectral cube by lowering the spectral resolution, and by taking the median of several hyperspectral cubes [28].

2.4. Spectroscopic inversion algorithm

Concentrations of CH\(_4\), CO\(_2\), H\(_2\)O, and temperature along each LOS must be obtained simultaneously from the spectroscopic data since all these variables influence the spectral intensity that reaches the camera. However, this process is ill-posed as multiple temperatures and concentration distributions along each LOS exist that, when substituted into the measurement equations, produce nearly identical spectra. In the limiting case of a monochromatic measurement and an optically-thin gas with negligible background intensity, Eq. (8) becomes a Fredholm integral equation of the first kind, in which the integral is \(\kappa_{\eta, k}(s) I_0 [T(s)]\), and its inversion has infinite solutions. While considering multiple wavenumbers and optically thick lines reduces the ambiguity, the problem remains
ill-posed. Consequently, it is necessary to introduce prior information regarding a presumed distribution shape for the species concentration and temperature along the LOS. In the case of turbulent plumes, the distributions are well-represented by Gaussian profiles instead of uniform profiles, and Grauer et al. [29] shown that this choice produces a more accurate mass flow rates. Consequently, species and temperature distributions are parameterized according to

$$

\chi_k(s) = \chi_{k,\text{max}} \exp \left( -\frac{s^2}{2\sigma^2} \right), \quad T(s) = (T_{\text{max}} - T_{\text{amb}}) \exp \left( -\frac{s^2}{2\sigma^2} \right) + T_{\text{amb}},

$$

where $\sigma$ is the characteristic plume width, $\chi_{k,\text{max}}$ and $T_{\text{max}}$ are the peak molar fraction and peak temperature, respectively, and $T_{\text{amb}}$ is ambient temperature. The plume thickness is specified based on the observed plume height along the chord length in the camera image and is assumed to be the same for temperature and all species mole fractions; this approximation becomes more reasonable in flows dominated by turbulent mixing. Maximum likelihood estimates for the species and temperature distribution parameters, $x = [X_{\text{CH4, max}}, X_{\text{CO2, max}}, X_{\text{N2O, max}}, T_{\text{max}}]^T$, are found by

$$
x_{\text{MLE}} = \arg \min_x \left\{ \beta(x) - b \right\}^T \Gamma_b^{-1} \left[ \beta(x) - b \right] \right\}

$$

where $b$ contains the measured spectral intensities, $b^*$ is corresponding modelled intensities generated using the measurement model described in Section 2.1-2.3, and $\Gamma_b$ is the measurement error covariance matrix, which is modelled as diagonal where each element is the corresponding camera noise variance for each spectral bin. The parameters in $x_{\text{MLE}}$ are then used to infer the column densities of the species-of-interest using Eq. (4).

2.5. Velocimetry algorithm

The column densities are then combined with projected, intensity-weighted velocities for the pixels along the control boundary to produce the mass fluxes. The velocities are inferred from the apparent motion of intensities from successive broadband images. As already noted, the camera frame rate, 400 Hz using the full-frame, is much faster than the framerate of the transformed hyperspectral images. The average intensities of the broadband images vary with the OPD, so each broadband image is rescaled by its average pixel intensity prior to processing.

The normalized broadband images are analyzed using the Horn-Schunck optical flow algorithm [24]. In this approach, temporal changes in the rescaled pixel brightness, $E$, between successive images is attributed solely to advection, so

$$

\frac{DE}{dt} = \frac{\partial E}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial E}{\partial y} \frac{\partial y}{\partial t} + \frac{\partial E}{\partial t} = 0

$$

and therefore

$$

E_x u + E_y v = -E_t

$$

where $E_x = \partial E/\partial x$, $E_y = \partial E/\partial y$, $E_t = \partial E/\partial t$ and $u$ and $v$ are the $x$ and $y$ velocity components. The derivatives are estimated from two successive image frames using a finite difference approximation, and are stored in vectors $e_x$, $e_y$, and $e_t$.

For a flow field consisting of $N_v$ pixels, Eq. (17) produces a system of $N_v$ equations and $2N_v$ unknown velocity components,

$$

[e_x, e_y] [u \ v]^T = AV = -e_t

$$

where $e_x = \text{diag}(e_x)$ and $e_y = \text{diag}(e_y)$ and $V$ contains the unknown velocities. This underdetermined set of equations is closed using a Tikhonov smoothness prior at each pixel,

$$

\begin{bmatrix}
  A & \lambda I_{uv} \\
  \lambda I_{uv} & \lambda L
\end{bmatrix}
\begin{bmatrix}
  e_x \\
  \lambda L_{uv}
\end{bmatrix}
\begin{bmatrix}
  u \\
  v
\end{bmatrix}
= \begin{bmatrix}
  -e_t \\
  0
\end{bmatrix}

$$

where $L$ is a discrete approximation of the gradient operator and $\lambda$ is the regularization parameter, which is chosen heuristically.

3. CFD Proof-of-concept study

The viability of this measurement procedure, in particular the approach used to infer the species column densities from the recorded intensity spectrum, is assessed using simulated measurements of the plume of a flare in a crosswind. The simulation was carried out using Arches, a CFD-LES that includes the simplified oxidation mechanism proposed by Westbrook and Dryer [30], and an LES turbulence sigma model. Radiative transfer is modelled using the discrete ordinates method with total gas properties inferred from the Sarofim and Hotell gas emittance charts [31]. The flare is 10 m high and has an inner diameter of 102 mm. Methane is
injected at 25.6 g/s into the air at 298 K and a crosswind velocity of 3.056 m/s and then ignited. The computational domain is 3.5 m × 3 m × 5 m, discretized into 1.3 × 10^7 elements of 5 cm × 5 cm × 5 cm, and the coordinate system origin is located at the center of the left-side of the flare tip.

Since the objective of this analysis is to assess the accuracy of the species column density, local CE is defined according to

\[
CE_{\text{local}} = \frac{\rho_{\text{CO}_2}/M_{\text{CO}_2}}{\rho_{\text{CO}_2}/M_{\text{CO}_2} + \rho_{\text{CH}_4}/M_{\text{CH}_4}}
\]  

where the column densities are computed from Eq. (4). Fig. 4 shows the local CE at one instant in the CFD simulation. The red line indicates the 800 K isotherm, which roughly corresponds to the flame envelope.

The CFD data was used to generate synthetic IFTS spectra with the model described in Section 2. Equipped with the standard telescope, the Hyper-Cam MW has a field of view of 6.4° × 5.1°. For each pixel location on the focal plane array, a vector was projected through the CFD domain following a pinhole camera analogy. The model spectral data is down-sampled to the camera spectral resolution using Eq. (11). The plume thickness parameter, σ, was assumed to be 1 m along the chord length based on the plume height, and the gas state parameters are found using Eq. (15).

The CO\(_2\) and CH\(_4\) column number densities corresponding to the measurement plane in Fig. 4 are plotted in Fig. 5 (left). The high concentration of unburned CH\(_4\) below the flare is due to the aerodynamic fuel stripping mechanism. In both cases, the IFTS-inferred concentrations are in reasonable agreement with the CFD ground truth values and generally reproduce the trends in CO\(_2\) and CH\(_4\) column density with z. When these concentrations are substituted into Eq. (20), they accurately reproduce the ground-truth local CE derived from the CFD data as shown in Fig. 5 (right).

Differences between the CFD- and IFTS-inferred column densities can be attributed to the ill-posedness of the underlying inference problem and model error introduced by assuming a Gaussian distribution along each LOS for each species concentration and the temperature distribution (i.e., the well-mixed plume approximation.) Were the species concentration inferred through absorption spectroscopy, the overall column density would be less sensitive to the parameterization of the species concentration and temperature along each LOS. In the limiting case of an isothermal gas, and assuming that the intensity measured at a given wavelength is due only to the kth species,

\[
\ln\left(\frac{I_{h,k}/I_{h,0}}{I_{h,0}}\right) = \int_0^\infty k_{h,k}(s)\,ds \propto \rho_k
\]

in which case the parameterization assumed for \(k_{h,k}(s) \propto N_k(s)\) does not matter. In the case of emission spectroscopy and a non-isothermal gas, however, the parameterizations of \(T(s)\) and \(X_k(s)\) are connected through the emission term in the RTE and the ideal gas law, assuming negligible background intensity and an optically thin line, and again that the measured spectral intensity is due to an individual species,

\[
I_{h,k} = \int_0^L k_{h,k}(s)I_{h,k}[T(s)]\,ds
\]

so accurate retrieval of \(k_{h,k}(s)\), and hence \(X_k(s)\) and \(\rho_k\), depend on the accuracy of the presumed distributions for both \(X_k(s)\) and \(T(s)\).

Further insights into this aspect of the inference problem are found by plotting temperature and species mole fractions along LOS at −0.2, 0.3, and 0.5 m, as shown in Fig. 6. At z = −0.2 m, the CE is overpredicted because the CH\(_4\) column density is underestimated as shown in Fig. 5. Although the temperature profile does not follow a Gaussian distribution, it is close to ambient temperature and does not generate a significant error in the inferred column density. Instead, as the plume thickness assumed for both species is broader than the ground truth, both peak concentrations are underestimated. However, the CO\(_2\) ground truth distribution has a small “bump” before the plume centre that aligns with the temperature peak, increasing the spectral intensity over the CO\(_2\) bands and, consequently, the inferred CO\(_2\) concentration. At z = 0.3 m, the inferred CE is close to unity, while the ground truth CE is lower. This is because the CH\(_4\) concentration is underpredicted, as shown in Fig. 5.

Fig. 6 shows that the distribution shapes for temperature and CO\(_2\) are generally similar, as one would expect since the combustion reaction releases CO\(_2\) and locally increases the gas temperature. For the same reason, high concentrations of CH\(_4\) correspond to low concentrations of CO\(_2\). As the inferred temperature is higher than the CFD temperature in regions of high CH\(_4\) concentration, the inferred CH\(_4\) concentration is lower than the ground truth concentration to generate an equivalent spectral intensity over the CH\(_4\) bands. At z = 0.5 m, the inferred CE is close to the ground truth, but the temperature is overpredicted, and the column densities of both CO\(_2\) and CH\(_4\) are underpredicted. Nevertheless, the ill-posedness of the inference problem and the assumption of Gaussian profiles having a specified width results in significant differences between the inferred mole fractions along a LOS and the CFD ground-truth, these errors are, to a large extent, “integrated out” when obtaining the column densities and the local CE, suggesting the overall feasibility of this technique.

4. Experimental analysis

The viability of this measurement technique is next assessed by measuring gas concentrations and flow rates in an experimental setting, using a Telops Hyper-Cam MW described in Section 3, with a measurement resolution of 4 cm\(^{-1}\). This is done in two stages: first, the Hyper-Cam is used to recover the concentration and flow rates of a heated mixture of CH\(_4\)/CO\(_2\) without combustion. Next, the instrument is used to analyze the plume of a lab-scale steam and air-assisted flare.

4.1. Heated vent experiments

Heated plumes of a CH\(_4\)/CO\(_2\) mixture were generated using the apparatus shown schematically in Fig. 7. Flow rates were con-
controlled using two mass flow controllers (Brooks GF40) to produce a CH₄/CO₂ vol mixture fraction of 0.5 while maintaining a total volumetric flow of 10 standard litres per minute (SLPM). The gas flowed through a heated line before being discharged from a 19 mm diameter nozzle. The gas temperature was measured using a K-type thermocouple in the gas flow at the nozzle discharge, which was maintained at approximately 40 K above the ambient temperature of 294 K (21 °C).

The gas plume discharged against a background of four 15 cm × 15 cm aluminum plates arranged vertically behind the plume. The plates are painted matt black (Krylon k01602 Ultra-Flat black) with a spectral emissivity ranging between 0.95 and 0.97 over the measurement spectrum of the IFTS and approximated as perfectly black in the radiative transfer model. The plates were maintained at 273 K (0°C) using a water/ethylene glycol mixture, which produced a background intensity one may expect when carrying out a field measurement on a cloudy day. This temperature is higher than the ambient dew point, which ensured no condensation formed on the plates. The IFTS aperture is located 2.1 m away from the plume centerline and 2.2 m away from the background plates.

Fig. 8 shows sample IFTS images corresponding to wavenumbers of 2336 cm⁻¹ and 2453 cm⁻¹, along with the spectral intensity corresponding to the median of 50 datacubes of the indicated pixel, which shows emission from both the 2300 cm⁻¹ CO₂ band and the 2900 cm⁻¹ CH₄ band. The plume is most visible in the 2336 cm⁻¹ image, but is also visible at 2453 cm⁻¹, which is outside this band, due to scene change artifacts. The light/dark patterns shift with wavenumber according to Eq. (14).

The hypercubes are analyzed as follows. First, pixels from outside of the plume, shown in green, are used to infer the background intensity and ambient CO₂ concentration and temperature.

Fig. 5. (left) CO₂ and CH₄ column densities along the control surface shown in Fig. 4; (right) the corresponding local CE from Eq. (22). Dashed lines indicate the LOS positions in Fig. 6.

Fig. 6. Plot of CFD-derived and IFTS-inferred species concentrations for the pixels indicated in Fig. 4. Top row z = −0.2; middle row z = 0.3; bottom row z = 0.5 m.
The ambient gas is modelled as homogenous between the background and the camera aperture. The RTE measurement model is used to recover the ambient state for the lines-of-sight corresponding to the background pixels. Probability distributions of the background temperature, ambient CO₂ temperature, and concentration are shown in Fig. 9. Ambient H₂O was also inferred from the background spectrum; however, the spectral intensity has the same order of magnitude as the measurement noise, and the result did not converge, showing that ambient H₂O does not affect the measurements over the pathlength between the plume and the camera.

Mean values for these parameters are then incorporated into the RTE model used to analyze the pixels along the control surfaces (red dashed lines) shown in the hyperspectral images in Fig. 8. The peak molar fractions and temperature were inferred using Eq. (15) for a characteristic plume width, σ, of 6 cm, based on the visible plume in the images. Recovered CO₂ and CH₄ peak mole fractions and temperature profiles inferred on the control surface “M” are plotted in Fig. 10. The peak molar fractions follow a roughly Gaussian distribution with respect to θ, which supports

---

**Fig. 7.** Schematic of the heated vent experiment.

**Fig. 8.** Hyperspectral images of the 50%/50% CH₄/CO₂ plume at 2336 cm⁻¹ and 2453 cm⁻¹, and corresponding measurement spectra for pixels from the background and within the plume. The red dashed lines in the hyperspectral image shows the integration surface, while background pixels used to obtain the distributions in Fig. 9 are shown in green. The spectrum is found by averaging 50 datacubes.

**Fig. 9.** Probability density functions for CO₂, background temperature, and ambient gas temperature inferred using the background (green) pixels shown in Fig. 8 (left).
the Gaussian plume hypothesis for this scenario. The peak mole fraction for CH₄ is noisier compared to that of CO₂, which may be due to the weaker signal and lower signal-to-noise ratio over the spectral region corresponding to the 2900 cm⁻¹ band, compared to the 2300 cm⁻¹ band.

The velocity profile along the control surfaces are inferred using the optical flow algorithm described in Sec. 2.6. Fig. 10(b) shows the averaged y-component velocity of 2600 timesteps calculated using sequential broadband images evaluated over OPDs of x ∈ [-1.247 mm, -0.424 mm], and x ∈ [0.424 mm, 1.247 mm], which avoids artifacts caused by the peak interferogram fluctuations when the mirror is close to its centre position. Combining the velocity profile with the species column densities results in the mass flow rates shown in Table 1, which are in good agreement with the values inferred from the mass flow controllers, as well as the equivalent CE derived by substituting the mass flow rates into Eq. (7). Note that the CE calculation is sensitive to the shape of the velocity profile, which is used to weigh the column densities according to their location relative to the velocity field, but not the overall velocity magnitude, since the mass flow rate appears in the numerator and denominator in Eq. (7).

4.2. Laboratory-scale steam- and air-assisted flare

The IFTS is next used to characterize the plume of a laboratory-scale flare, shown in Fig. 11. The flare consists of an annular burner having an inner diameter of 11.3 mm, a wall thickness of 0.7 mm, and an outer diameter of 22.9 mm. Fuel is supplied to the annulus, while the assisting fluid, air or steam, is injected through the central tube. The flare is confined by vertical mesh screens to prevent the flame from drifting while allowing air entrainment into the flame and plume. Flare combustion products are collected by an exhaust hood with its flow controlled by a venturi valve to maintain turbulent flow and keep the combustion products well-mixed. The exhaust duct contains a probe that directs a sample of exhaust gas to a photoacoustic extintiometer (PAX), which measures black carbon mass concentrations. The four background plates were aligned horizontally due to the width of the flare plume at 60 cm above the burner tip and used to maintain a background temperature of 3.5 °C. More information about the experimental setup can be found in Ref. [14, 32].

Methane is supplied to the flare with a flow rate of 5 SLPM. The flare CE is adjusted by varying the assisting fluid flow rate,
Fig. 13. Intensity spectra for assisted flares: (a) 120 SLPM air; 75 SLPM air; 30 SLPM air, and (d) 29 g/s steam. Blue and red curves correspond respectively to pixel locations within and outside of the plume, at locations shown in Fig. 12.

### Table 2

Plume sample species molar fractions, soot concentration and mass flow. Species that were not detected in the sample were excluded from the table (C$_2$H$_6$, C$_3$H$_8$, CO, and H$_2$).

<table>
<thead>
<tr>
<th>Air [SLPM]</th>
<th>Soot [g/m$^2$] $\times 10^6$</th>
<th>$\chi_{CH_4}$ $\times 10^3$</th>
<th>$\chi_{CO_2}$ $\times 10^3$</th>
<th>$m_{\text{soot}}$ [g/s] $\times 10^6$</th>
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<tr>
<td>30</td>
<td>0.014</td>
<td>0.005</td>
<td>0.743</td>
<td>0.012</td>
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<td>75</td>
<td>0.046</td>
<td>0.020</td>
<td>0.737</td>
<td>0.015</td>
</tr>
<tr>
<td>120</td>
<td>0.234</td>
<td>0.129</td>
<td>0.601</td>
<td>0.085</td>
</tr>
<tr>
<td>28.7$^*$</td>
<td>2.030</td>
<td>0.220</td>
<td>0.535</td>
<td>0.751</td>
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</table>

$^*$ Steam [g/s].

### Table 3

Results summary of the inferred mass flows using the IFTS versus values obtained by the MFC settings and the GC concentrations.

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<th>GC/MFC</th>
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<tr>
<td></td>
<td>$m_{CH_4}$ [g/s]</td>
<td>$m_{CO_2}$ [g/s]</td>
</tr>
<tr>
<td>HV</td>
<td>0.060</td>
<td>0.162</td>
</tr>
<tr>
<td>Air 120</td>
<td>0.028</td>
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<tr>
<td>Air 75</td>
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<td>0.139</td>
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<td>Air 30</td>
<td>0.001</td>
<td>0.146</td>
</tr>
<tr>
<td>Steam</td>
<td>0.049</td>
<td>0.019</td>
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which is 30, 75, or 120 SLPM of air or 29 g/s of steam. Samples of the plume are collected into a Tedlar bag and analyzed using a gas chromatograph (GC) (Agilent, 7890B). CH$_4$, C$_2$H$_6$, C$_3$H$_8$, CO$_2$, CO, and H$_2$ concentrations inferred from this instrument are summarized in Table 2 for the flare operating conditions, which are used to calculate the flare CE. These measurements confirm that the flare CE drops with increasing the air and steam flow rates. The molar fractions are converted into mass flow rates and a CE, listed in Table 3, using the equations proposed in Ref. [22].

Fig. 12 shows spectral intensity maps at 2336 cm$^{-1}$ and 3013 cm$^{-1}$, aligned with the CO$_2$ and CH$_4$ VR bands, respectively, for a flare plume with 120 SLPM of air. The control surface is shown in red. The similarity of these results shows that the plume appears to be well-mixed at the measurement height. The relative intensity of the images shows that, as is the case for the heated vent.
experiments, the CH₄ emission spectrum has a significantly lower signal-to-noise ratio compared to the CO₂ emission spectrum.

Spectra corresponding to the pixel locations within and outside the plume are plotted in Fig. 13. In the air-assisted cases, the visible flame length increases as the air flow rate decreases. The IFTS measurement position is maintained relative to the flare nozzle, so the position of the control surface changes relative to the flame front. Methane spectral lines are clearly apparent for the 120 SLPM air-assisted case, indicating inefficient combustion. The CH₄ emission spectrum is less pronounced at 75 SLPM air-assisted case, while the CO₂ emission is stronger since the control surface has moved to a hotter region of the flame. In 30 SLPM air-assisted case, the entire spectrum is uniformly shifted above the background intensity, due to broadband emission from soot within the flame that would otherwise be oxidized were the measurement carried out further downstream. For the steam-assisted case, both H₂O and CH₄ emission lines are particularly pronounced, suggesting highly inefficient combustion in this scenario. In summary, the intensity spectra are qualitatively consistent with the expected trends in CE and GC concentration measurements in Table 2.

Next, the IFTS data is analyzed to obtain quantitative mass flow rate estimates and overall flare CE. Background pixels were analyzed to obtain ambient CO₂ concentration and ambient gas and background temperatures as described in Section 4.1, which were then incorporated into the RTE model. The peak concentrations for CO₂ and CH₄ for 120 SLPM air-assisted case are plotted in Fig. 14(a), along with the temperature profile. Each point corresponds to the concentrations inferred from the median of 50 sequential spectra.

Since the gas temperature of the flare plume is higher than that of the heated vent, one may expect a lower signal-to-noise ratio in the data, leading to a more robust estimate of the species column densities. On the contrary, however, Fig. 14(a) shows that the inferred peak concentrations for CH₄ are more irregular than the heated vent case. For these measurements, the dynamic range of the camera becomes an issue. Specifically, the integration time of the camera must be decreased to avoid saturating the spectrum corresponding to CO₂ emissions, but this significantly degrades the signal-to-noise ratio over the CH₄ spectral band. In contrast to the heated plume, the CO₂ peak molar fraction does not follow a Gaussian distribution; rather, it appears to be lower in the center of the plume than at the edges. This effect may be due to the fact that air is injected through the center tube of the burner.

The velocity profile is calculated using the same procedure described in Section 4.1 and is plotted in Fig. 14(b). The mass flow of each species is found by combining the column densities and velocity profile, which are shown in Table 3. The inferred CH₄ mass flow is generally close to the ground truth flow, while the CO₂ mass flow is severely over-predicted. Comparing the measured spectrum for the pixel with the highest inferred CO₂ peak concentration and the model spectra for the 120 SLPM air-assisted case provides further insight into the origins of this problem. Fig. 15 shows spectral features that are adjacent to the CO₂ band, but do not correspond to emission spectra of any expected combustion species. These features also appear in the spectra corresponding to 75 SLPM air-assisted case. They also appear in the spectra from background pixels (i.e. outside of the exhaust plume) for these scenarios, although they are not as intense as for LOS through the plume. These spectral features did not appear in the heated vent experiments, so their origin remains unknown.

The situation is compounded when soot contributes to the emission spectrum, as seen in Fig. 13(c) for the 30 SLPM air-assisted case, since soot is not accounted for in the spectroscopic model. This result suggests that the displacement of the measurement window from the flare combustion zone may play a critical role in the feasibility of this approach, and further experimentation is needed to identify strategies that avoid contamination of the spectrum with soot incandescence. In a real flare measurement, this effect can be mitigated by choosing control surfaces farther from the flame, although with a corresponding decrease in measurement intensity and signal-to-noise ratio. Additionally, the greater contrast between the background and the plume should facilitate the inference. On the other hand, the background spectra can be challenging, although clear sky can be modelled as a blackbody at 255 K, the emission from ambient species needs to be considered because of the long path length.
5. Conclusions

While flaring is assumed to convert hydrocarbons into CO₂ with high efficiency, there is growing awareness that this may not always be the case, particularly under conditions of severe crosswind and when excessive air and steam is used to suppress black carbon emissions in assisted flares. Mid-infrared hyperspectral imaging presents an opportunity to quantify the combustion efficiency of operating flares through remote, stand-off measurements. In this approach, CE is inferred from a mass balance of carbon-containing species within the flare plume. Mass flow rates, in turn, are found by combining column densities, obtained through a spectroscopic emission model, with velocities obtained from an optical flow algorithm.

This study evaluated the viability of this approach through numerical and experimental analysis. Simulated measurements were carried out on a CFD-LES of a flare in a cross-flow. Intensities generated using the radiative transfer equation were transformed into intensity spectra, which in turn were inverted to recover distributions of temperature, CO₂, and CH₄ concentrations along various lines-of-sight, which are presumed to be Gaussian. These distributions were transformed into column densities and used to define local CEs for each pixel along a control surface. The inferred distributions are, in some cases, significantly different from the CFD simulations, highlighting the ill-posed nature of this inverse problem, but the recovered CEs are much closer to the ground truth.

The approach was then experimentally-assessed using a heated vent of CH₄ and CO₂, and a laboratory-scale air- or steam-assisted flare. In the case of the heated vent experiment, the mass flow rates inferred from the hyperspectral data closely matched known flow rates. In addition, this experiment highlights how hyperspectral data can be used to obtain background intensity and ambient gas concentrations outside of the plume, parameters that feature in the spectroscopic model. In the case of the air- and steam-assisted flare, the intensity spectra are qualitatively consistent with the expected trends in CE. The IFTS-inferred CH₄ mass flow rates were close to values inferred from the known flow rates of the reactants and gas chromatography measurements on the combustion products. On the other hand, CO₂ mass flow is significantly overpredicted, possibly due to measurements anomalies in the spectral data.

Overall, the results establish the viability of hyperspectral imaging as a way to quantify flare CE and also highlight the challenges of this approach and the need for further experimentation to develop best practices to avoid adverse measurement conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

RB Miguel: Methodology, Investigation, Formal analysis, Writing – original draft. S Talebi-Moghaddam: Methodology, Software. M Zamani: Investigation. C Turcotte: Resources, Writing – review & editing. KJ Daun: Conceptualization, Methodology, Supervision, Writing – review & editing, Project administration, Supervision, Funding acquisition.

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Flaring plays a critical role in reducing the environmental impact of upstream oil and gas processing by converting methane and other gaseous hydrocarbons into CO2, which has a lower global warming potential. This process is highly efficient under ideal conditions but efficiency may be significantly lower under certain scenarios such as fuel stripping under crosswind and emission of volatile organic compounds and unburned fuels due to over-aeration or over-steam in assisted flares. This study assesses the potential of using imaging Fourier transform spectrometers (IFTs) to directly measure combustion efficiency by combining species column densities estimated from a spectroscopic model with intensity-weighted velocities found using an optical flow model. Simulated measurements using a computational fluid dynamics (CFD)-large eddy simulation of a flare in a crosswind are used to establish the technique’s viability, followed by experimental measurements on a heated gas vent to validate the optical flow model. Finally, preliminary measurements are carried out on a laboratory-scale steam- and air-assisted flare. While the simulated measurements and heated vent experiments support the feasibility of this approach, experimentally-derived spectra from the lab-scale flare were contaminated with artifacts attributed to turbulent fluctuations, which complicates the quantitative interpretation of the IFTS data.