Abstract

• Quantitative optical gas imaging (QOGI) using mid-wavelength infrared (MWIR) cameras permits standoff measurements, particularly under hazardous conditions, and can be used to quantify methane concentrations and fluxes over large areas.

• Pixel intensities of MWIR images are related to the column density and temperature of methane (or other species) along a corresponding line-of-sight through a plume.

• Velocity field is inferred from the apparent evolution of a sequence of images.

• Column densities combined with the velocity field yield mass flux estimates.

• Current and emerging QOGI technologies consist of:
  • single-channel cameras that use a single bandpass filter
  • multispectral (MS) cameras that use multiple bandpass filters
  • hyperspectral (HS) cameras that generate a highly-resolved spectrum for each pixel.

Key Questions:
• What are the advantages of a multispectral camera over a single-channel camera?
• How do uncertain plume temperatures affect mass flux estimates?

• Camera measurement model/QOGI algorithm is developed and validated using images of methane vents captured with a FLIR GF320 camera.

• Inferred mass flow rates are similar to those found using a QL320 QOGI tablet.

• Model is used to analyze simulated data generated with a CFD-large eddy simulation of a methane plume.

• Results highlight the improved accuracy that may be obtained using cold-filtered multispectral cameras, which are emerging as an alternative to traditional single-channel cameras.

Acknowledgements

• This research is carried out under the Canadian Emissions Reduction Network (CanERIC) program and NSERC’s FlareNet.

• Special thanks to Kirk Osadetz from CMC Research Institutes and Matthew Johnson from Carleton University for lending us their OGI cameras.
Assessing QOGI Camera Technologies for Methane Emission Quantification

Michael Nagorski, Rodrigo B. Miguel, Sina Talebi-Moghaddam, Kyle J. Daun
Department of Mechanical and Mechatronics Engineering, University of Waterloo

Simulation Setup
• CFD - large eddy simulation of a 2 cm diameter well-mixed vent of gases
• RTE applied to CFD output to generate synthetic images
• Images contaminated with random noise
• Measurement model applied to synthetic images to infer column densities, velocity fields, and mass fluxes

Single-Channel MWIR Cameras
• Methane and other gases are transparent in the visible wavelengths but emit and absorb over mid-wavelength infrared (MWIR) wavelengths
• Single-channel MWIR cameras contain a single bandpass filter which transmits light onto the detector, producing an image of the gas given a temperature difference exists with the background

Measurement Model
• The integrated density of gas along a line-of-sight (LOS) is the column density
• Pixel intensity is related to the column density and temperature of methane (or other species) along the LOS through the radiative transfer equation (RTE)

Lucas-Kanade Optical Flow
• Relates brightness gradients and velocity components at a pixel-by-pixel level between successive images
• Divides images into small windows and assumes uniform velocity within each window
• Velocities are combined with column densities to obtain mass flux

Experimental Setup
• Stack apparatus that vents gas mixtures at controlled flow rates and temperatures
• Temperature-controlled black plate background
• Capable of validating QOGI estimates

QOGI Technologies
• FLIR GF320/GF620/GFx320
• FLIR QL320
• Telops FAST-M150

Multispectral Cameras
• Contain multiple filters to produce additional spectral information of the scene (i.e. gases)

Single-Channel MWIR Camera Spectrum

Measurement Model

Lucas-Kanade Optical Flow

Experimental Setup

QOGI Technologies
Assessing QOGI Camera Technologies for Methane Emission Quantification

Michael Nagorski, Rodrigo B. Miguel, Sina Talebi-Moghadam, Kyle J. Daun
Department of Mechanical and Mechatronics Engineering, University of Waterloo

In-house QOGI Algorithm + GFx320 and QL320 Experimental Results

- Ambient temperature methane (22°C), 20 second measurement averages, 5 SLPM and 10 SLPM flow rates

- In-house QOGI algorithm results in 16% and 28% error on average
- Average velocity of methane was between 0-0.9 m/s so calm wind speed setting in QL320 should be used, but resulted in 55% and 42% error on average
- Normal wind speed setting resulted in 14% and 19% error on average

Heated Methane Experimental Results

- Single-channel measurements assume that gas is at ambient temperature, which may not be the case (e.g. tanks)
- Conducting single-channel measurements on heated methane (55°C at exit) violates this assumption and yields poor QOGI estimates

Simultaneous Temperature Inference

- Multispectral imaging can be used to infer additional unknown parameters (e.g. additional species column densities or gas temperature)

<table>
<thead>
<tr>
<th>Test Case</th>
<th>5 SLPM Result [SLPM]</th>
<th>10 SLPM Result [SLPM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL320 using 49.5°C (T_{\text{amb}}) (max), calm wind speed</td>
<td>0.96 (81% error)</td>
<td>1.8 (82% error)</td>
</tr>
<tr>
<td>QL320 using 49.5°C (T_{\text{amb}}) (max), normal wind speed</td>
<td>2.3 (54% error)</td>
<td>4.4 (56% error)</td>
</tr>
<tr>
<td>QL320 using 22°C (T_{\text{amb}}) (actual), calm wind speed</td>
<td>8.6 (72% error)</td>
<td>14 (40% error)</td>
</tr>
<tr>
<td>QL320 using 22°C (T_{\text{amb}}) (actual), normal wind speed</td>
<td>25 (400% error)</td>
<td>44 (340% error)</td>
</tr>
</tbody>
</table>

Conclusions

- Emerging MS IR camera technologies can expand the capabilities of QOGI when used appropriately, e.g. ONERA SIMAGAZ camera
- Experimentation and simulation of QOGI camera technologies in different scenarios can demonstrate the advantages and limitations of these technologies

Future Work

- Identify and explore more limiting scenarios for QOGI cameras and methods
- Field measurements in November 2021
- Improve optical flow estimates by exploring artificial intelligence and machine learning methods

Benefit of Cooled Optics

- Ambient temperature bandpass filters emit blackbody radiation over opaque wavelengths (Kirchoff’s law)
- Warm filter emission biases pixel intensities high and yields poor QOGI estimates

Simultaneous Temperature Inference

- Multispectral imaging can be used to infer additional unknown parameters (e.g. additional species column densities or gas temperature)

Simulation Parameters

\[ T_{\text{gas}} = 50^\circ \text{C} \]
\[ T_{\text{amb}} = 20^\circ \text{C} \]
\[ T_{\text{bg}} = 10^\circ \text{C} \]

Results

- QOGI Single-Channel: Invalid
- QOGI Multispectral: 0.0849 g/s
- CFD Ground-Truth: 0.0941 g/s

Conclusions

- Emerging MS IR camera technologies can expand the capabilities of QOGI when used appropriately, e.g. ONERA SIMAGAZ camera
- Experimentation and simulation of QOGI camera technologies in different scenarios can demonstrate the advantages and limitations of these technologies

Future Work

- Identify and explore more limiting scenarios for QOGI cameras and methods
- Field measurements in November 2021
- Improve optical flow estimates by exploring artificial intelligence and machine learning methods

Heated Methane Experimental Results

- Single-channel measurements assume that gas is at ambient temperature, which may not be the case (e.g. tanks)
- Conducting single-channel measurements on heated methane (55°C at exit) violates this assumption and yields poor QOGI estimates

Simultaneous Temperature Inference

- Multispectral imaging can be used to infer additional unknown parameters (e.g. additional species column densities or gas temperature)

Simulation Parameters

\[ T_{\text{gas}} = 50^\circ \text{C} \]
\[ T_{\text{amb}} = 20^\circ \text{C} \]
\[ T_{\text{bg}} = 10^\circ \text{C} \]

Results

- QOGI Single-Channel: Invalid
- QOGI Multispectral: 0.0849 g/s
- CFD Ground-Truth: 0.0941 g/s

Conclusions

- Emerging MS IR camera technologies can expand the capabilities of QOGI when used appropriately, e.g. ONERA SIMAGAZ camera
- Experimentation and simulation of QOGI camera technologies in different scenarios can demonstrate the advantages and limitations of these technologies

Future Work

- Identify and explore more limiting scenarios for QOGI cameras and methods
- Field measurements in November 2021
- Improve optical flow estimates by exploring artificial intelligence and machine learning methods