Velocimetry of Methane Emissions using Optical Gas Imaging

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Abstract

- Methane emissions must be quantified to develop policies that protect the environment without unduly penalizing Canada's oil and gas industry
- 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
- Mass flux estimates are found from column densities and the velocity field:
  - Column densities are related to the pixel intensities by a spectroscopic model
  - Velocity is inferred from the apparent evolution of turbulent artifacts within a sequence of images
- This work evaluates three candidate algorithms for velocimetry: the Horn-Schunck optical flow algorithm; the Lucas-Kanade optical flow algorithm; and image correlation velocimetry (ICV)
- Synthetic images are generated with a CFD-large eddy simulation (LES) of a methane plume, and the inferred velocity fields and mass fluxes are compared with ground-truth values
- Results demonstrate that each algorithm can accurately estimate the velocity fields and mass fluxes
- Future work will focus on experimental validation using a QOGI calibration apparatus at the University of Waterloo

Acknowledgements

- This research is carried out under the Canadian Emissions Reduction Innovation Network (CanERIC) program and NSERC's FlareNet

References

[1] B. K. P. Horn and B. G. Schunck, "Determining optical flow," *Artificial Intelligence*, vol. 17, no. 1-3, pp. 185–203, 1981.

[2] B. D. Lucas and T. Kanade, "An iterative image registration technique with an application to stereo vision," *IJCAI*, pp. 674–679, 1981.

[3] S. J. Grauer et al., "Gaussian model for emission rate measurement of heated plumes using hyperspectral data," *JQSRT*, pp. 125–134, 2018.

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1 Motivation

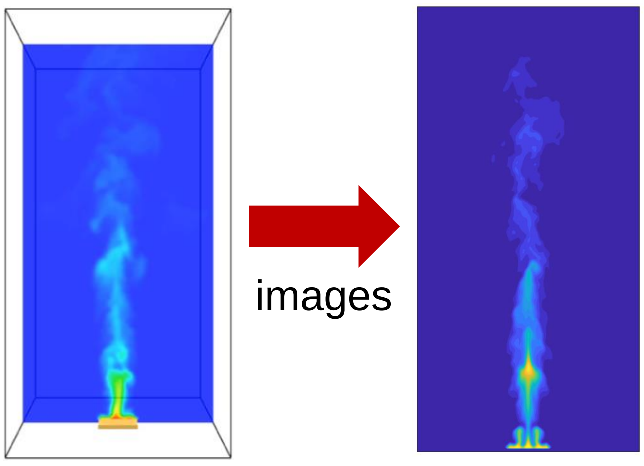
•QOGI can be used to conduct fence-line measurements of methane and other greenhouse gases over large areas

•Inferring the mass flux requires knowledge of the velocity field, from changes in a sequence of MWIR images

2 Simulated Methane Vent

•A CFD-LES software is used to simulate a 10 cm diameter heated vent of methane

•Synthetic images correspond to 2D slices of the temperature field at the midplane



video link

3 Horn-Schunck (HS) Optical Flow

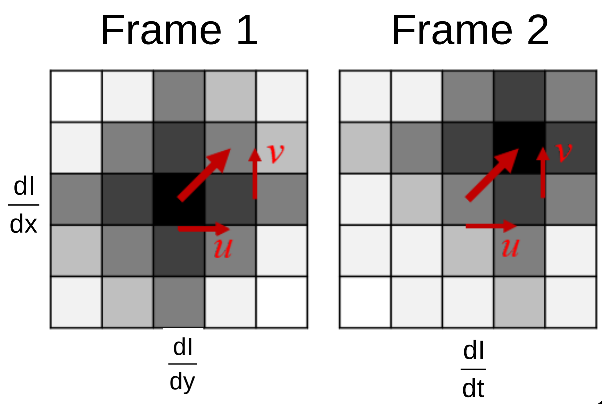
•Relates brightness gradients and velocity components at a pixel-by-pixel level between a pair of successive images

•Assumes velocity field varies smoothly in space to resolve underdetermined system of equations[1]

$$I_x u + I_y v + I_t = 0$$

$$\nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}$$

$$\nabla^2 v = \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}$$



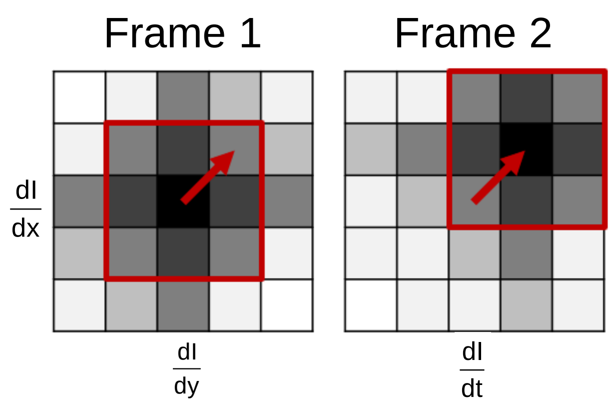
4 Lucas-Kanade (LK) Optical Flow

•Same optical flow equation as Horn-Schunck but divides the image into small sections of pixels and solves for the velocity field across these windows

•Assumes a uniform velocity in each window[2]

$$I_x u + I_y v + I_t = 0$$

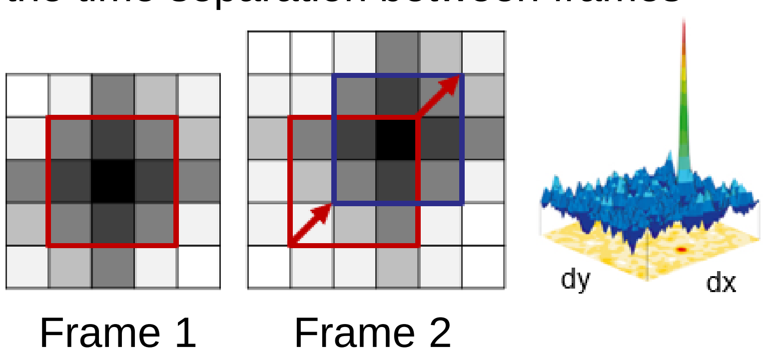
video link



5 Image Correlation Velocimetry (ICV)

•Frames are divided into interrogation windows and a displacement vector is calculated using cross-correlation techniques,

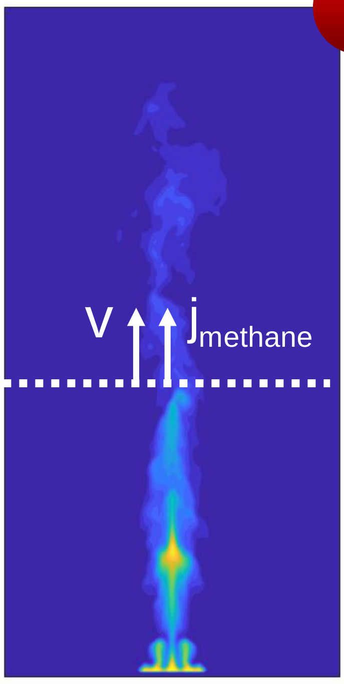
•Displacement vector is converted into a velocity using the time separation between frames



6 Mass Flux

•Methane mass flux is found by multiplying vertical velocity components with methane column density in each pixel and summing over a horizontal control surface

•This approach allows the velocity field results from each algorithm to be evaluated independently



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Velocity Component Error

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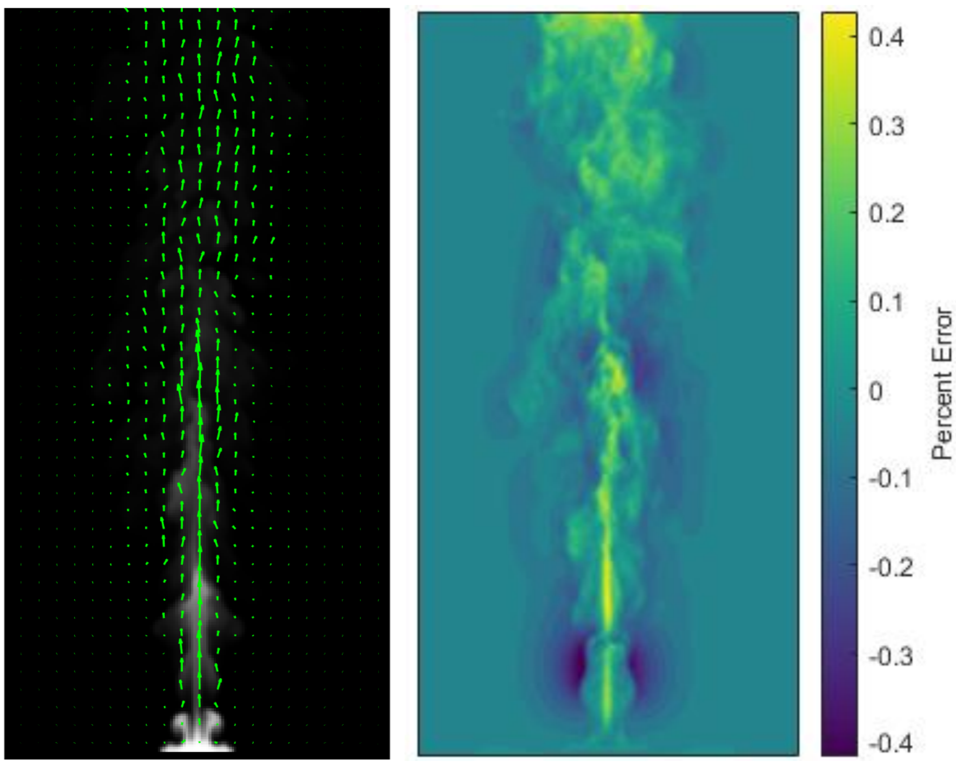
- Velocity field components inferred by each algorithm are compared to the CFD-LES ground-truth



Instantaneous Mass Flux

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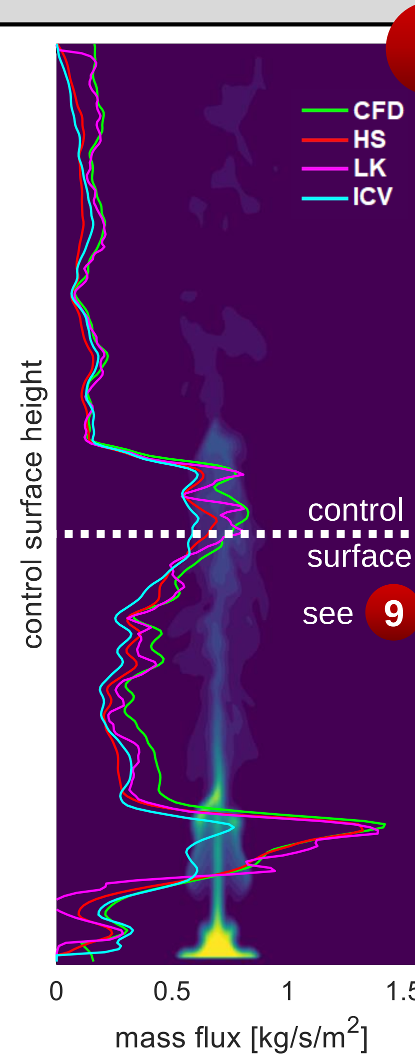
- Plotting the mass flux at various plume heights shows that it varies across the plume despite the constant mass flux boundary condition at the source
- Inferred mass flux estimates closely follow the CFD values irrespective of where a control surface is drawn
- All algorithms produce similar results



Time-Resolved Mass Flux

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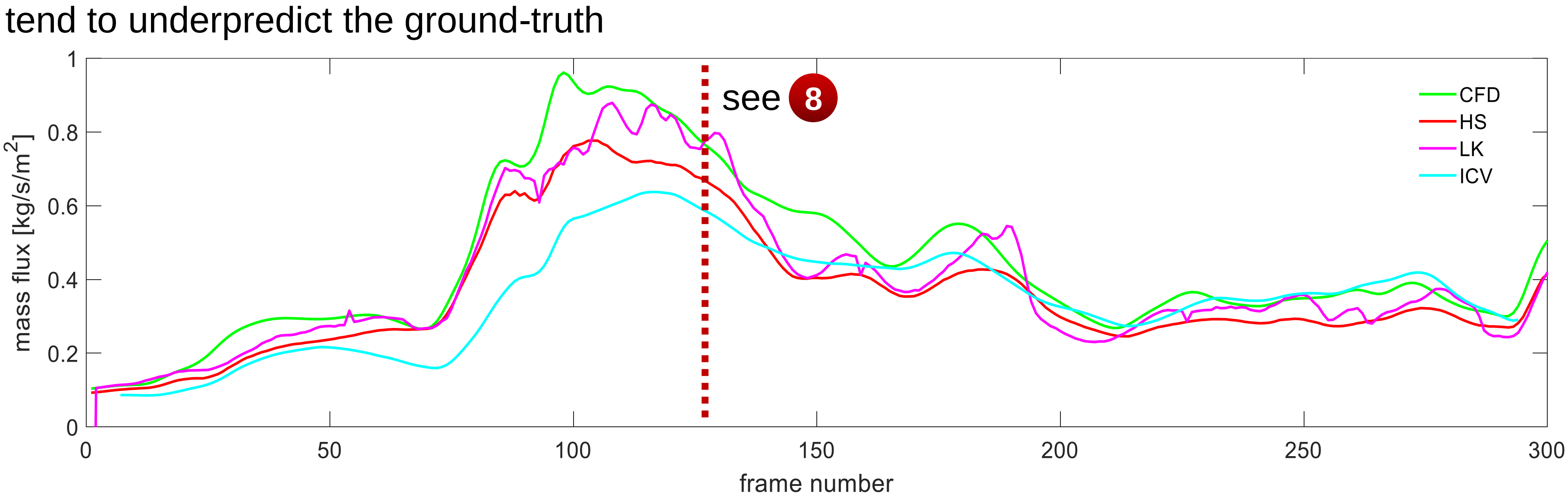
- Plotting the mass flux over time across a control surface illustrated above shows that the mass flux fluctuates over time due to the low velocity boundary condition in the simulation
- Each algorithm is generally accurate in estimating the total mass flux across the control surface although they tend to underpredict the ground-truth



Conclusions and Future Work

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- Each algorithm can accurately estimate the velocity fields and mass fluxes from a sequence of images
- The synthetic image model can be improved by projecting the 3D simulation volume into a 2D image using a spectroscopic model rather than extracting a 2D slice of temperatures from the mid-plume[3]
- Inferred velocity fields can be improved by implementing a Bayesian error model
- Optical flow and spectroscopic algorithms will be tested experimentally with a multispectral camera and a multi-component heated vent calibration apparatus at the University of Waterloo