

Density-Ratio Scaling of Air Entrainment in Short-Duration Hydrogen, Methane and Ammonia Jets.

Mr Andrew Crook, Dr Anthony Giles, Prof. Richard Marsh

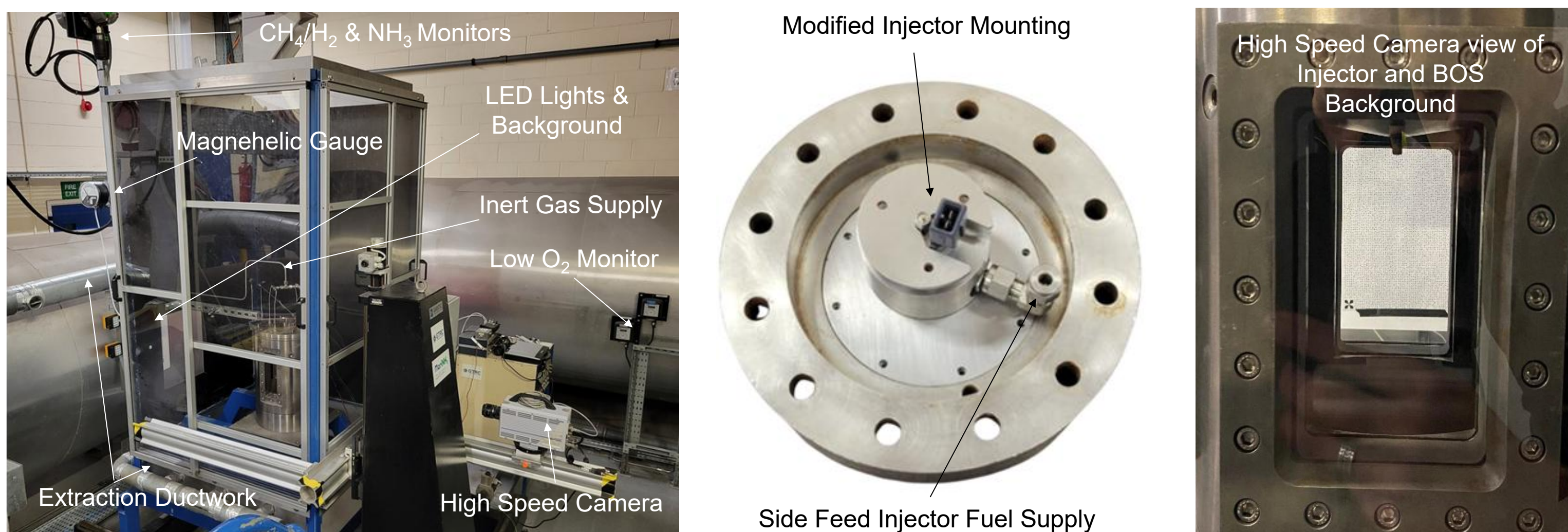
Gaseous fuel injection is not only a question of plume penetration, but also how effectively the fuel mixes with the surrounding gas. Hydrogen, methane, and ammonia produce visibly distinct BOS plume structures, but plume size alone does not indicate dilution.

This work extends previous BOS visualisation studies by using a large-orifice Westport injector, improved plume-boundary extraction and volume reconstruction to quantify air entrainment in transient gaseous jets.

Motivation and Method

Alternative gaseous fuels differ strongly in density, compressibility and optical plume behaviour. A method is required to compare not only plume size, but also the amount of ambient gas entrained during short-duration injection.

Experimental Setup



Methodology

Injector

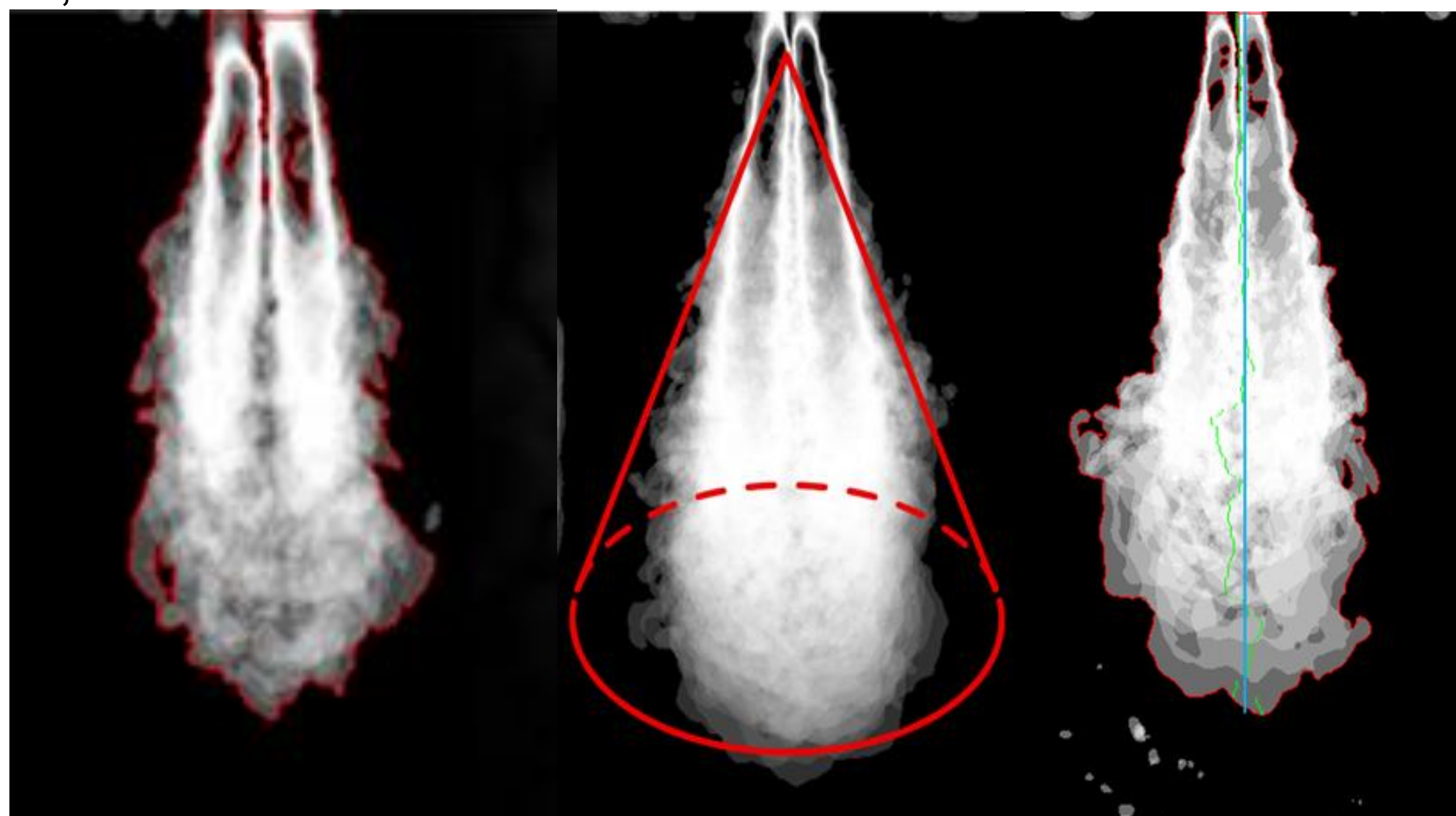
Westport IN03 MD injector,
3.9 mm nozzle diameter,
Injection Pressure
2- 5 Barg
Duration 2, 4 & 6 ms

BOS Visualisation

The comparative plume behaviour was visualised using Background Oriented Schlieren

Plume Boundary

The plume boundary was determined from BOS images using optical detectability. Red outline in the images below.



Plume Volume reconstruction via axisymmetric revolution

The plume volume was estimated by assuming the plume was axisymmetric about its centre line (shown in blue above, compared to the actual centre line in green) rather than a conical plume.

The local cross-sectional area was approximated as

$$A(y) = \pi r(y)^2.$$

The plume volume was then computed by discrete integration along the axial direction:

$$\sum_{y=y_{\min}}^{y_{\max}} \pi r(y)^2 \Delta y$$

By comparing the injected fuel volume with the measured plume volume, the degree of plume dilution and the amount of air entrained during the injection process can be quantified using the following equations.

$$\text{Entrainment } E = 1 - \frac{V_{\text{fuel}}}{V_{\text{plume}}}$$

$$\text{Dilution ratio } D = \frac{V_{\text{plume}}}{V_{\text{fuel}}}$$

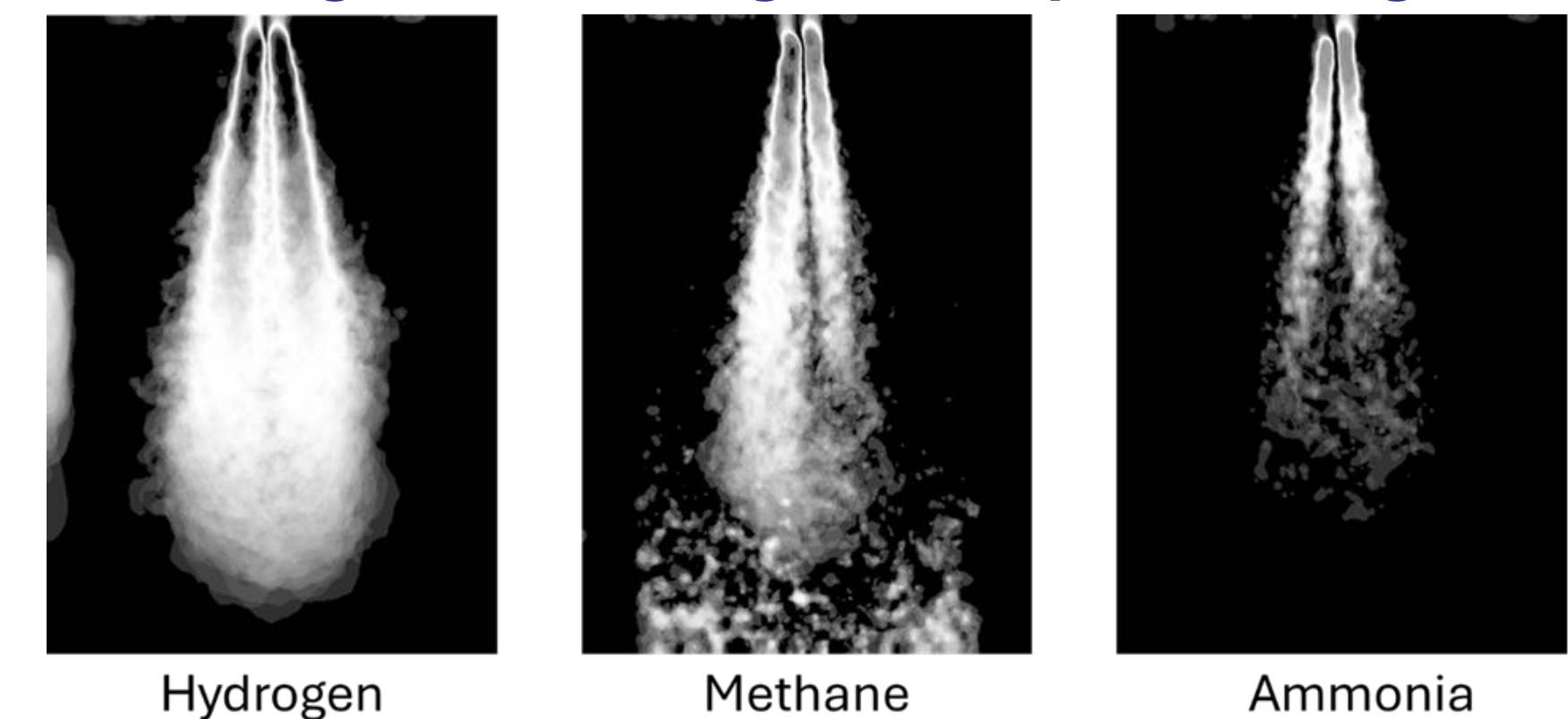
Numerical entrainment model

A simplified model was developed using classical turbulent jet entrainment theory to estimate plume growth and dilution. The instantaneous entrainment rate was obtained from the time derivative

$$\dot{V}_{\text{air}}(t) = \frac{dV_{\text{air}}(t)}{dt}$$

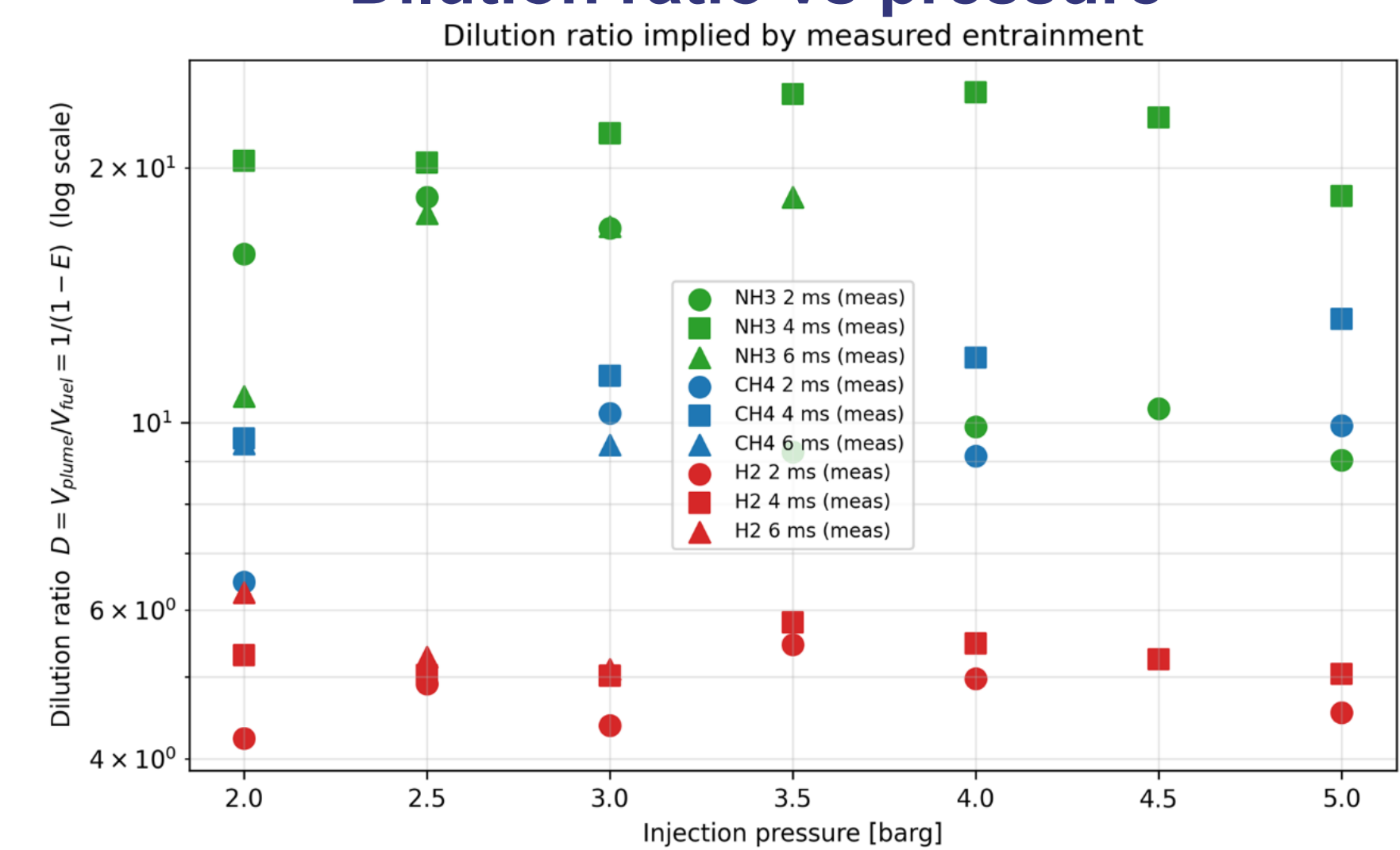
Results

4 Barg, 4 ms Averaged BOS plume images



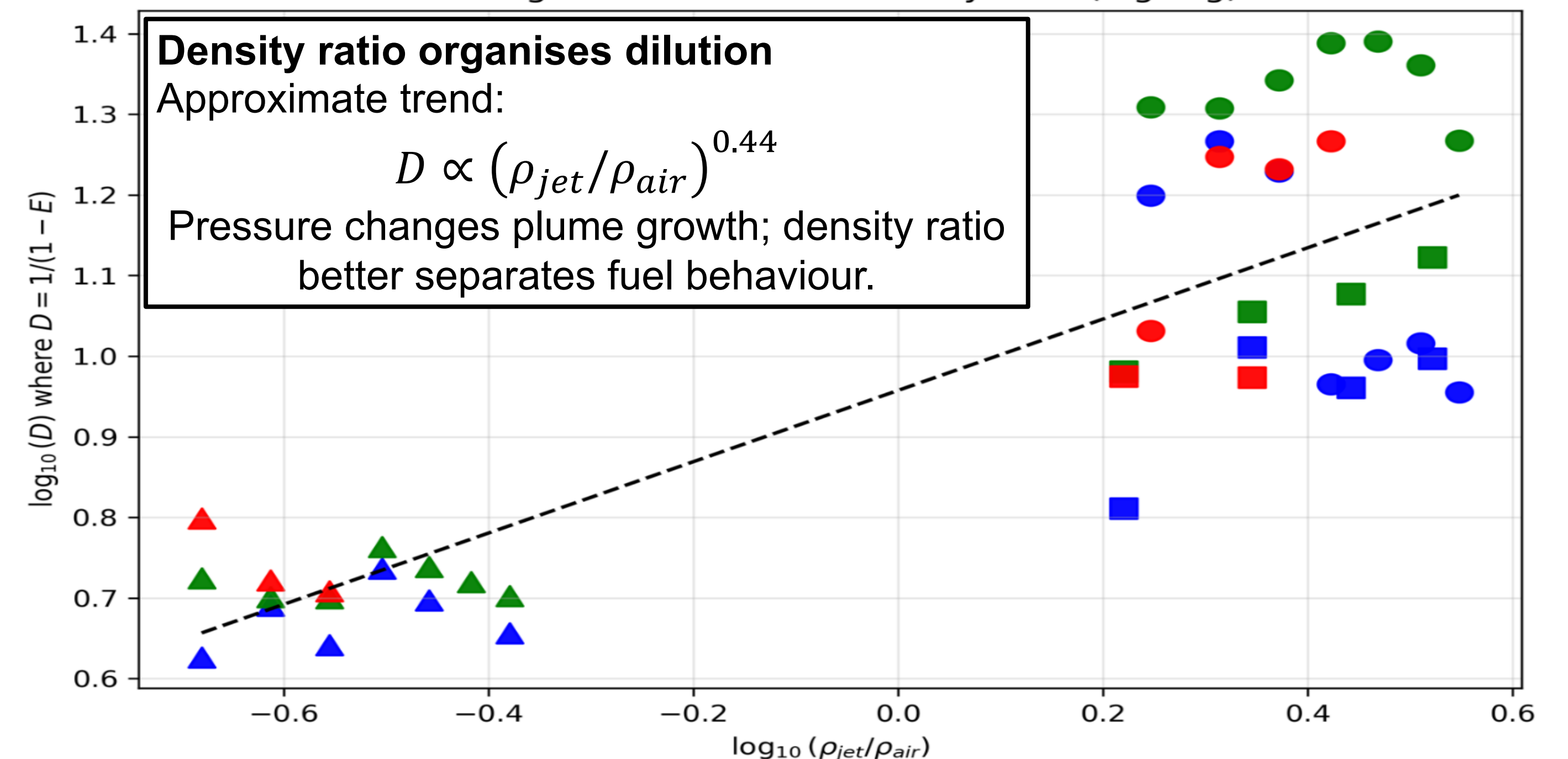
A larger visible plume extent does not necessarily mean higher dilution

Dilution ratio vs pressure



Dilution ratio vs density ratio

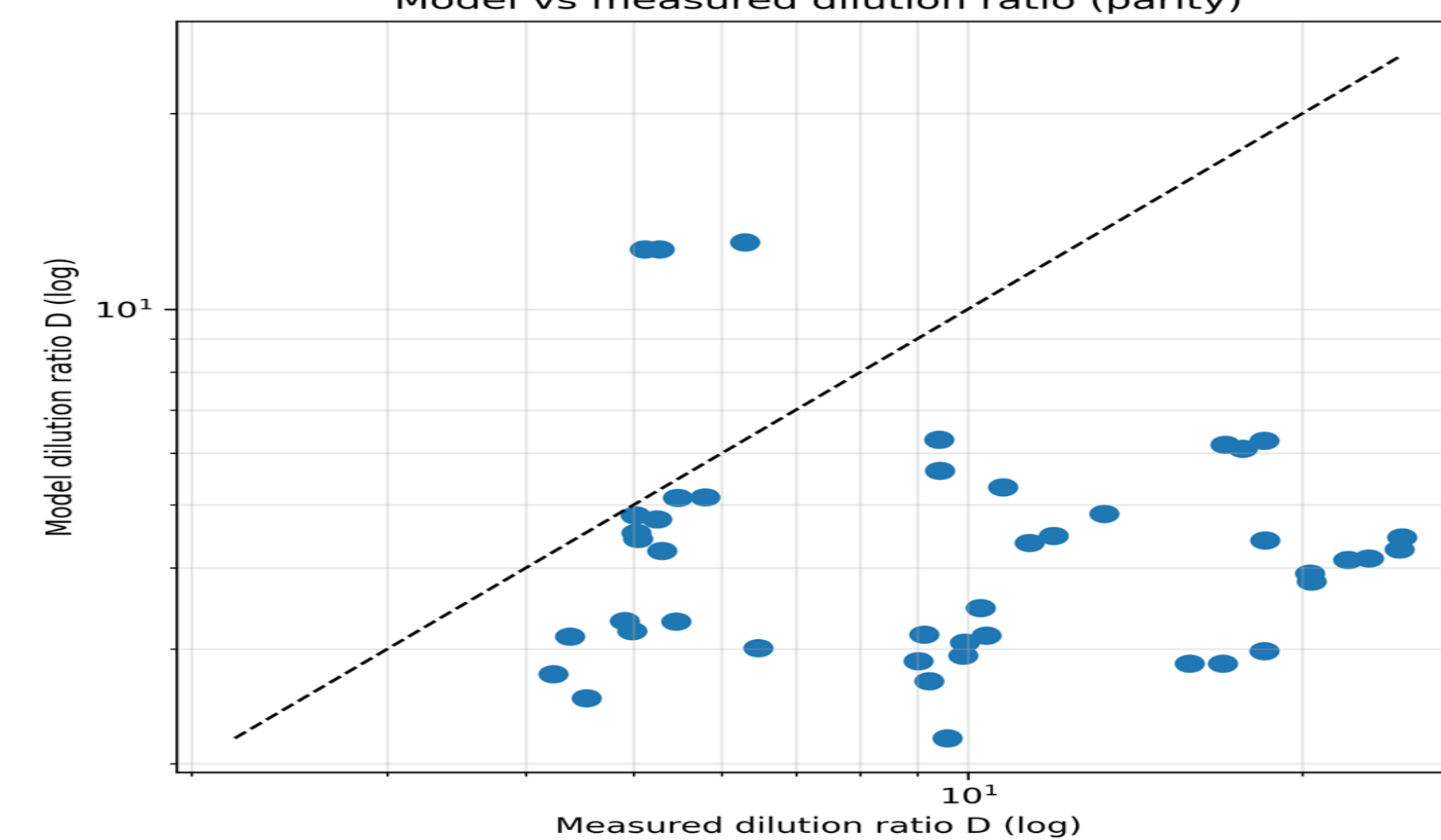
Scaling: dilution ratio vs density ratio (log-log)



Dilution is separated more clearly by fuel type and density ratio than by pressure

Model Comparison: trend captured, dilution underpredicted

Model vs measured dilution ratio (parity)



Model underprediction identifies the need for a more explicitly transient entrainment formulation

Key Conclusions

- Dilution Data**: NH₃ showed the highest dilution, and H₂ the lowest dilution, despite H₂ producing the largest visible plume.
- Dilution Parameter**: Density ratio provides a stronger organising parameter than injection pressure alone.
- Future Work**: Improve transient mixing physics of the simplified entrainment model.