Deep-Learning-Assisted Schlieren Analysis of Cellular Flame Morphology in Wall-Ignited NH_3/H_2 Combustion

MariNH3 — Clean, green ammonia engines for maritime

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Abstract

This work presents a fine-tuned Cellpose-SAM workflow for cellularity detection in wall-ignited 40%H_2/60%NH_3 Schlieren flame images at ambient conditions. Default CPSAM predictions were manually corrected to generate ground-truth masks, which were then used to adapt the model to the present CVCC imaging system. Validation on independent repeat-experiment images showed improved segmentation reliability and cell-count agreement compared with default model, enabling quantitative extraction of cell boundaries, centroids, projected areas and cell counts.

Introduction

1. **NH_3/H_2 blends are promising candidates for low-carbon marine combustion**, but ammonia's low reactivity and slow flame speed make stable flame propagation challenging. **Hydrogen enrichment improves combustion reactivity**, yet it can also promote flame-front wrinkling, intrinsic instabilities and cellular flame formation.
2. **Cellular flame structures are difficult to quantify from Schlieren images**, especially for non-spherical flames generated by wall-mounted ignition.

Research need

A robust and repeatable image-processing workflow is required to quantify cellular flame morphology in wall-ignited NH_3/H_2 flames, where conventional spherical-flame assumptions are not directly applicable.

Experimental Test Setup and Control

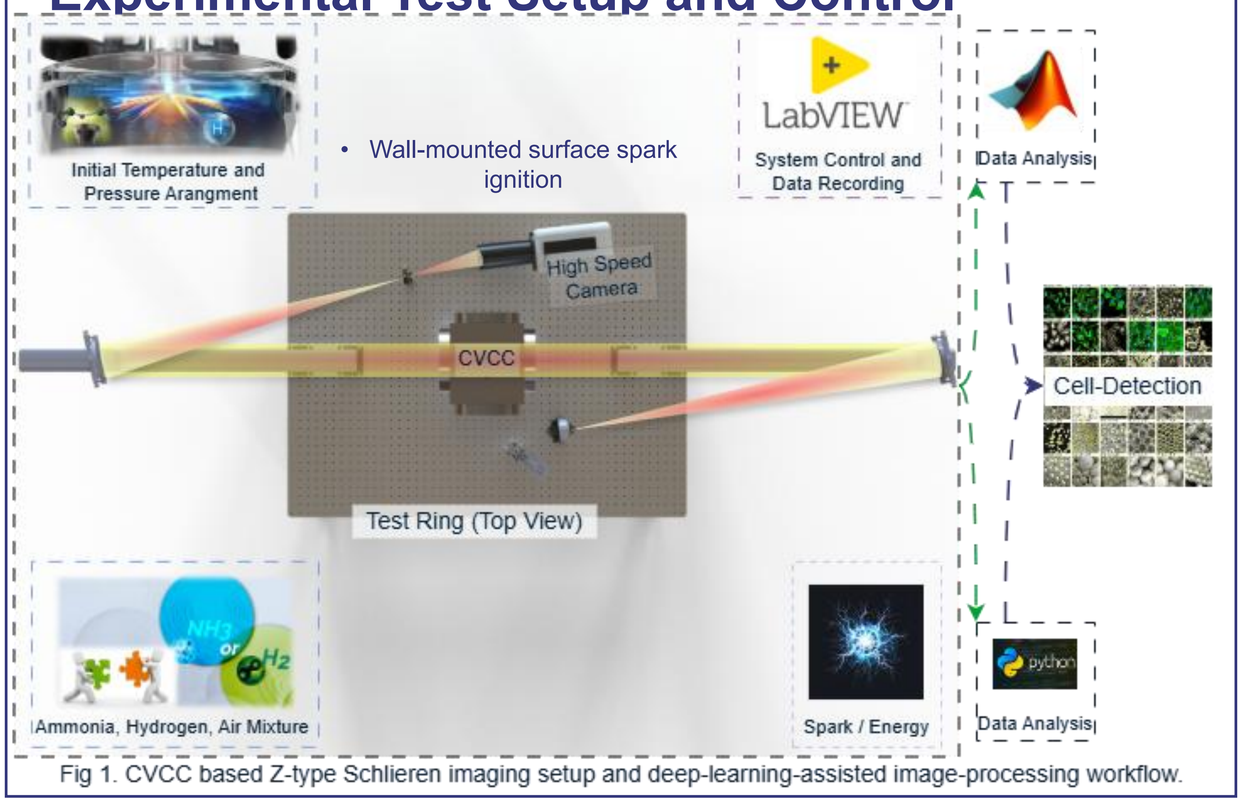
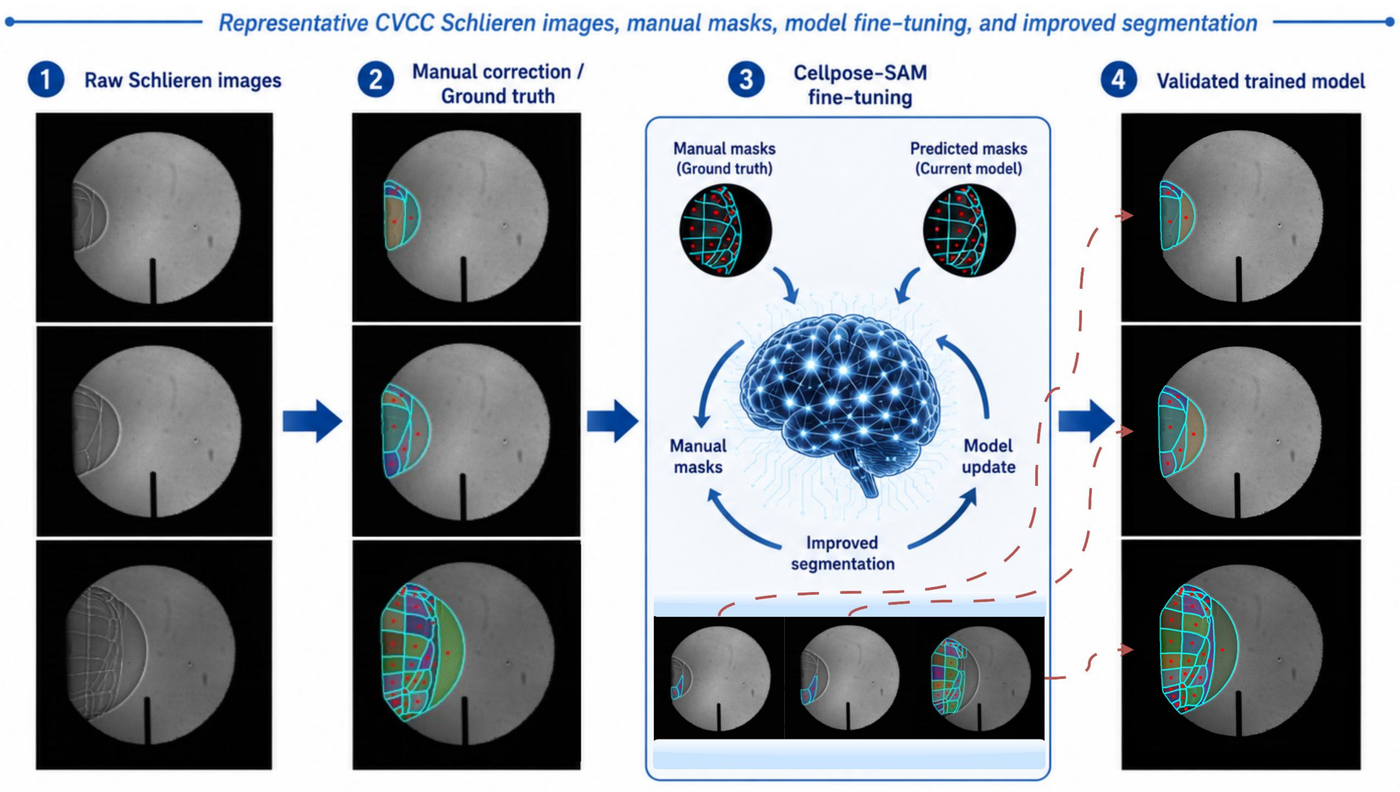
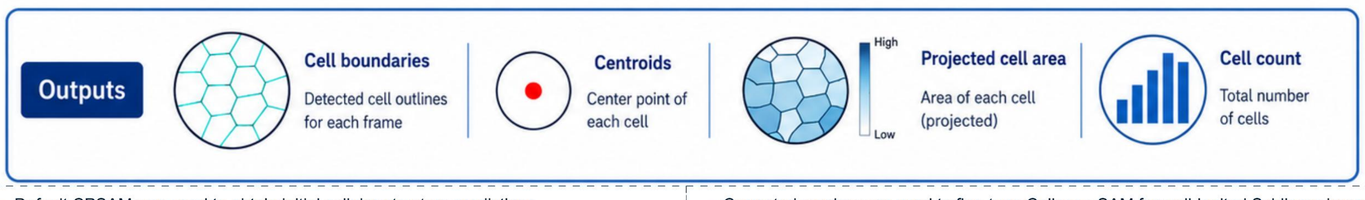


Fig 1. CVCC based Z-type Schlieren imaging setup and deep-learning-assisted image-processing workflow.

Image Processing, Cellularity Detection, and Results

Representative CVCC Schlieren images, manual masks, model fine-tuning, and improved segmentation





- Default CPSAM was used to obtain initial cellular-structure predictions.
- Manual correction generated ground-truth masks for flame-cell boundaries and centroids.
- Corrected masks were used to fine-tune Cellpose-SAM for wall-ignited Schlieren images.
- Extracted outputs include cell boundaries, centroids, projected cell area and cell count.

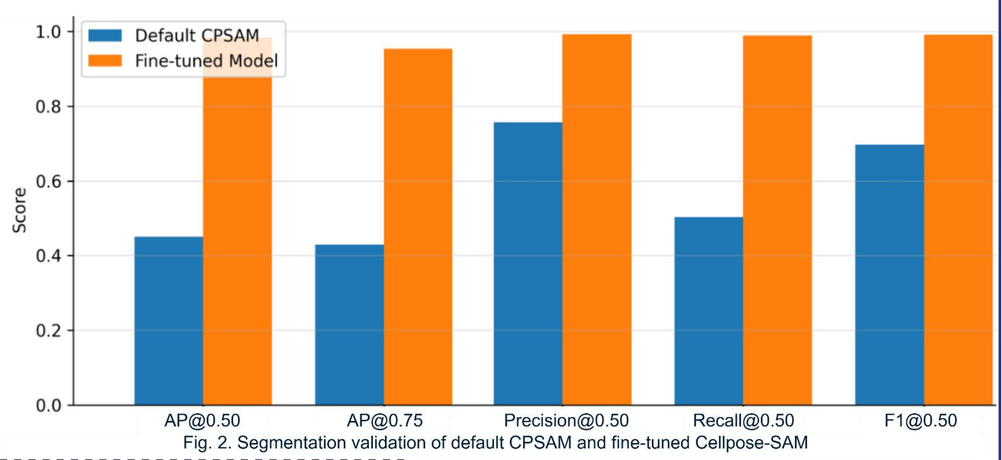


Fig. 2. Segmentation validation of default CPSAM and fine-tuned Cellpose-SAM

1) **IoU** measures the overlap between predicted and manual masks,
2) A match is accepted when **IoU ≥ 0.50** (or **0.75**).
3) **Precision** quantifies extra detections.
4) **Recall** quantifies missed cells.
5) **F1-score** balances precision and recall.

$$IoU = \frac{|P \cap G|}{|P \cup G|} \qquad Precision = \frac{TP}{TP + FP}$$

P= Predicted Mask, G= Manual Mask

FP = False Positive, TP = True Positive, FN = False Negative

$$Recall = \frac{TP}{TP + FN} \qquad F1 = \frac{2PR}{P + N}$$

- **The fine-tuned model clearly outperformed default CPSAM** in segmenting cellular flame structures
- **AP@0.50 improved from 0.45 to 0.98, while F1@0.50 improved from 0.70 to 0.99.**
- **Mean absolute cell-count error decreased from 3.42 to 0.33 cells/image**, showing much closer agreement with manual GT.

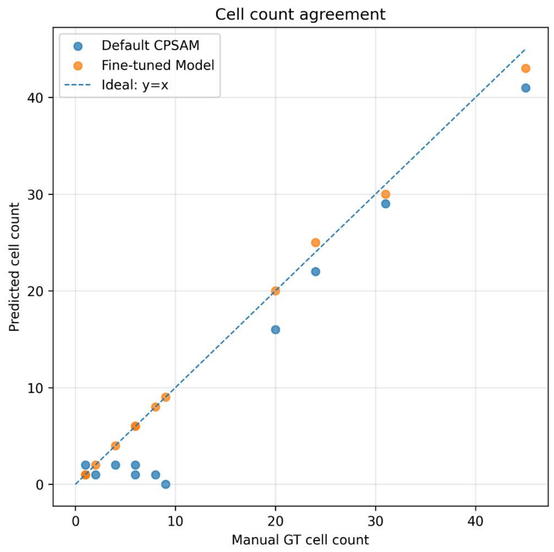


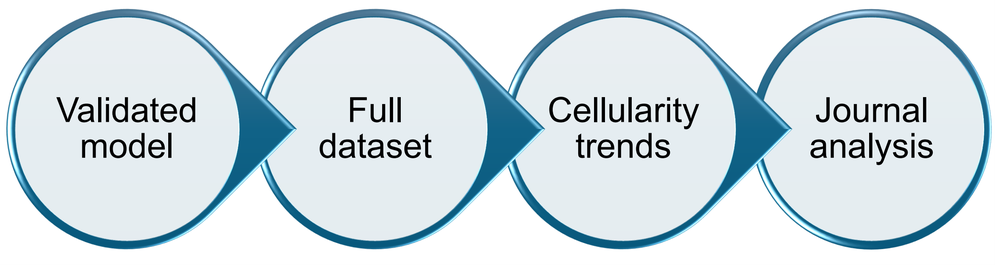
Fig. 3. Cell count agreement between predicted and manual annotations

Conclusion

- Cellpose-SAM was successfully fine-tuned for the present wall-ignited CVCC Schlieren imaging system.
- The fine-tuned model improved cellularity detection, increasing AP@0.50 from 0.45 to 0.98 and F1@0.50 from 0.70 to 0.99.
- The workflow provides a repeatable basis for extracting cellularity metrics from 40%H_2/60%NH_3 flame images.

Ongoing Studies

- Extend the validated model workflow to the full 1, 3 and 5 bar tests for 40%H_2/60%NH_3.
- Support future journal-scale analysis of NH_3/H_2 flame cellularity and instability.



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