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# Hydrogen Fuel Effects on Stability and Operation of Lean-Premixed and Staged Gas Turbine Combustors

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University Turbine Systems Research and Advanced Turbines Program Review Meeting
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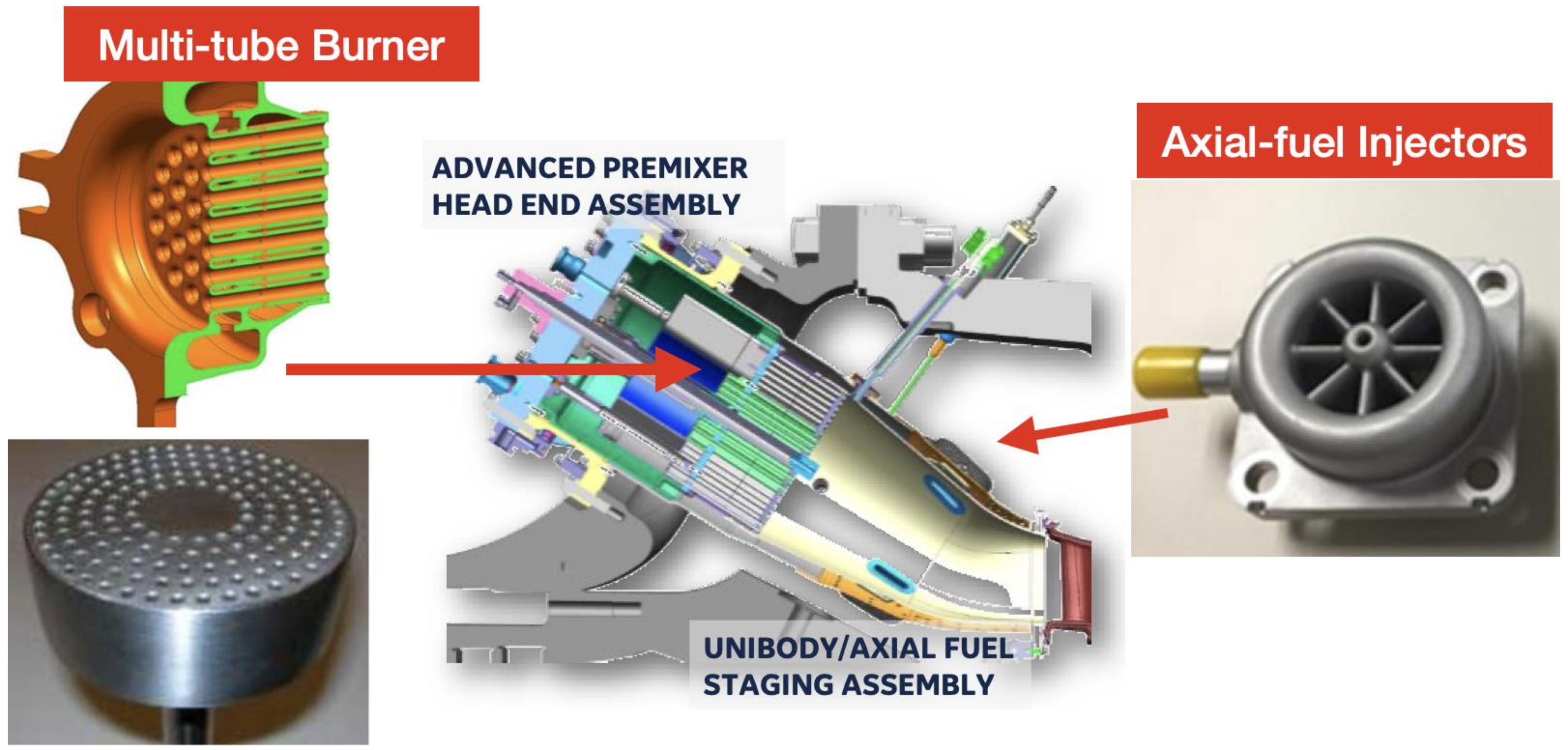
UNIVERSITY OF MICHIGAN

# Presentation Outline

- Background
- Project Objectives, Scope, and Technical Approach
- Experimental Update – Year 2 (OSU – Jeff Sutton)
- Computational Updates – Year 2 (UM – Vansh Sharma)

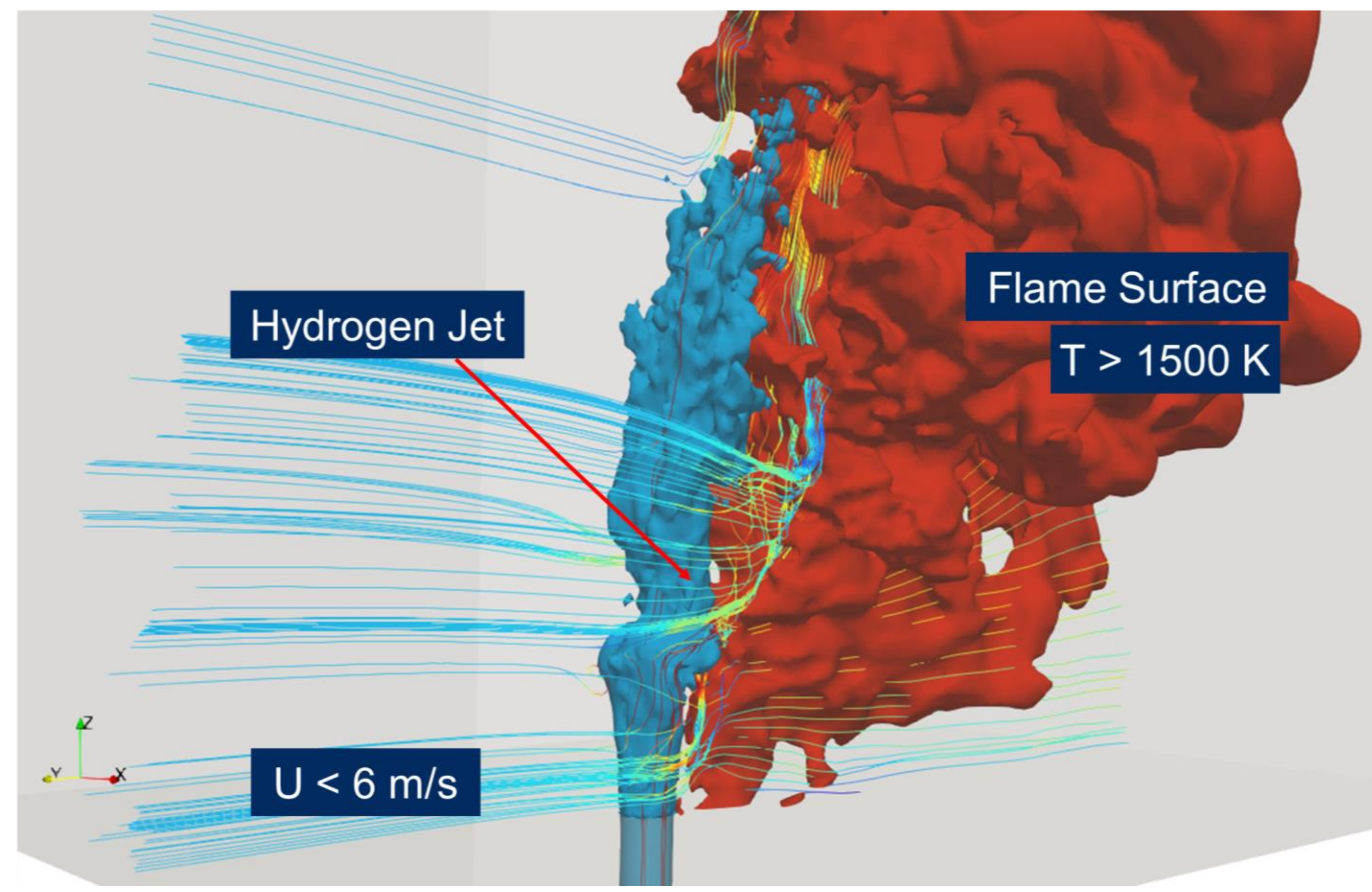
## The focus of this work is on core flow physics and flame processes that control combustor operation using hydrogen and hydrogen-containing (HC) fuels (i.e., $H_2$/HC blends)




*GE 9HA and 7HA machines with premixer/primary combustor and axial fuel staging*

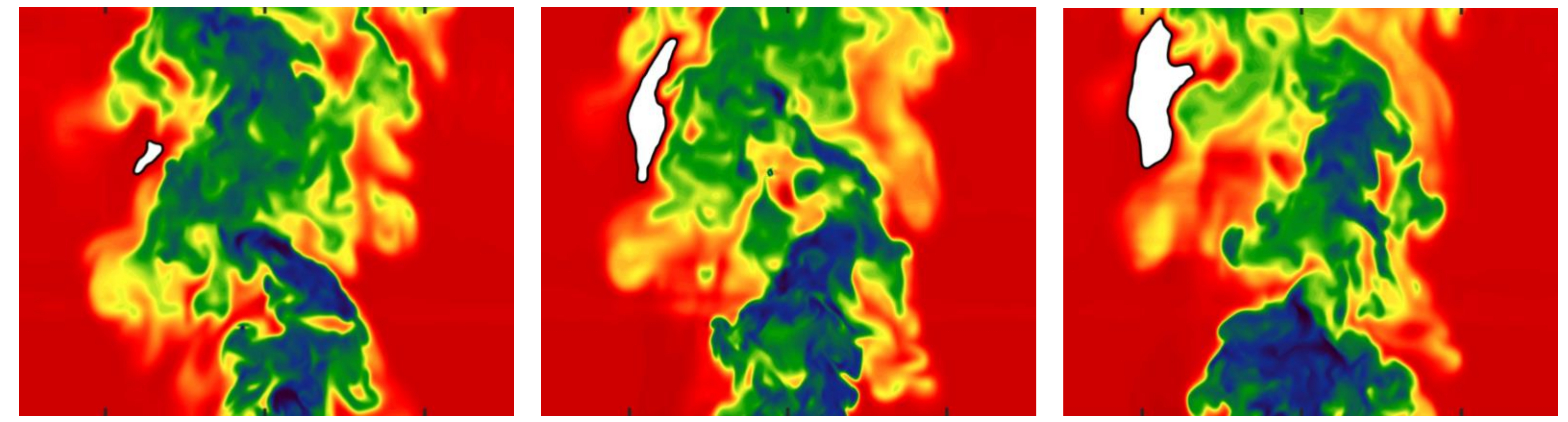
- Modern gas turbine designs use a lean, premixed primary burner and an axially staged secondary burner
- Significant development of hydrogen combustion technology with DoE support (up to 50% by vol)
- Limiting design constraints are dictated by hydrogen level

- Hydrogen is more reactive than HCs and has a high molecular diffusivity
- The limiting processes (flame holding, blowout, and flashback) are controlled by several fluids/heat transfer phenomena that interplay with one another
- There is a need for a broad set of experiments/computations to address issues
    - Advanced tools (laser diagnostics/DNS/LES)
    - Relevant conditions ($H_2$ content, pressure, confinement/wall effects, etc)




*Sharma, Tang, Raman, AIAA Scitech, 2024*

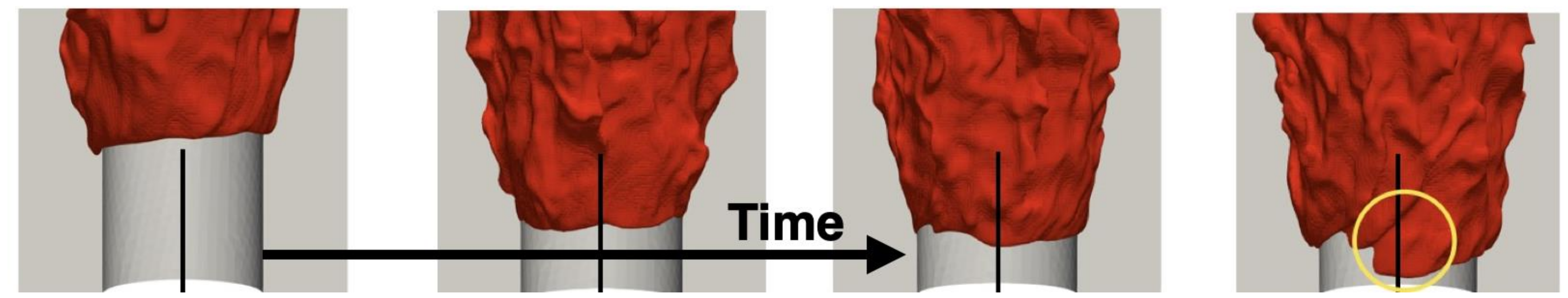
Technical Objectives: Joint experimental and computational effort to (1) investigate physics governing flame stabilization and flashback (2) develop predictive computational tools for simulating gas turbine combustion ***when burning hydrogen-containing (HC) fuels***



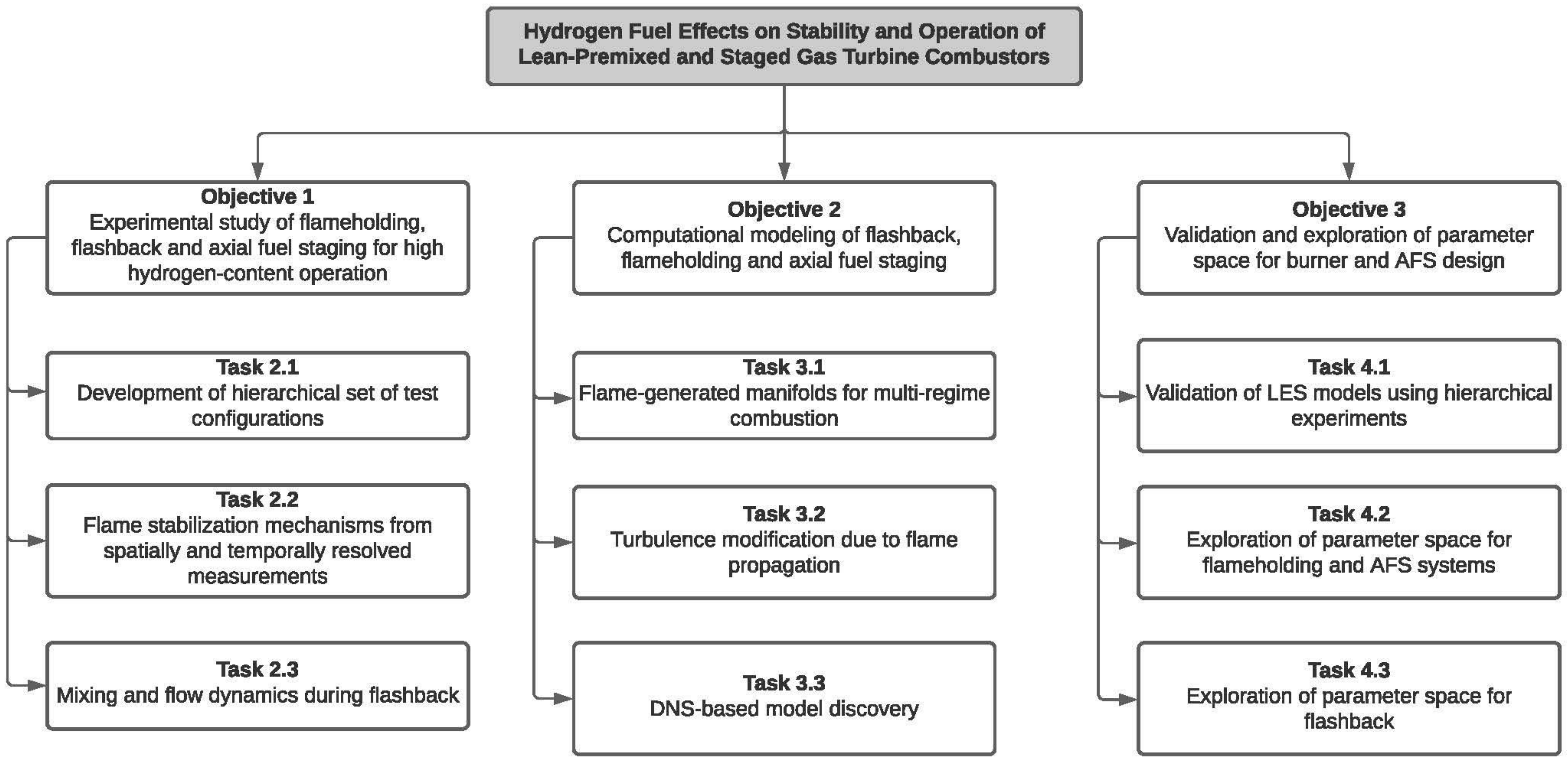
*Time-resolved temperature fields during auto-ignition*

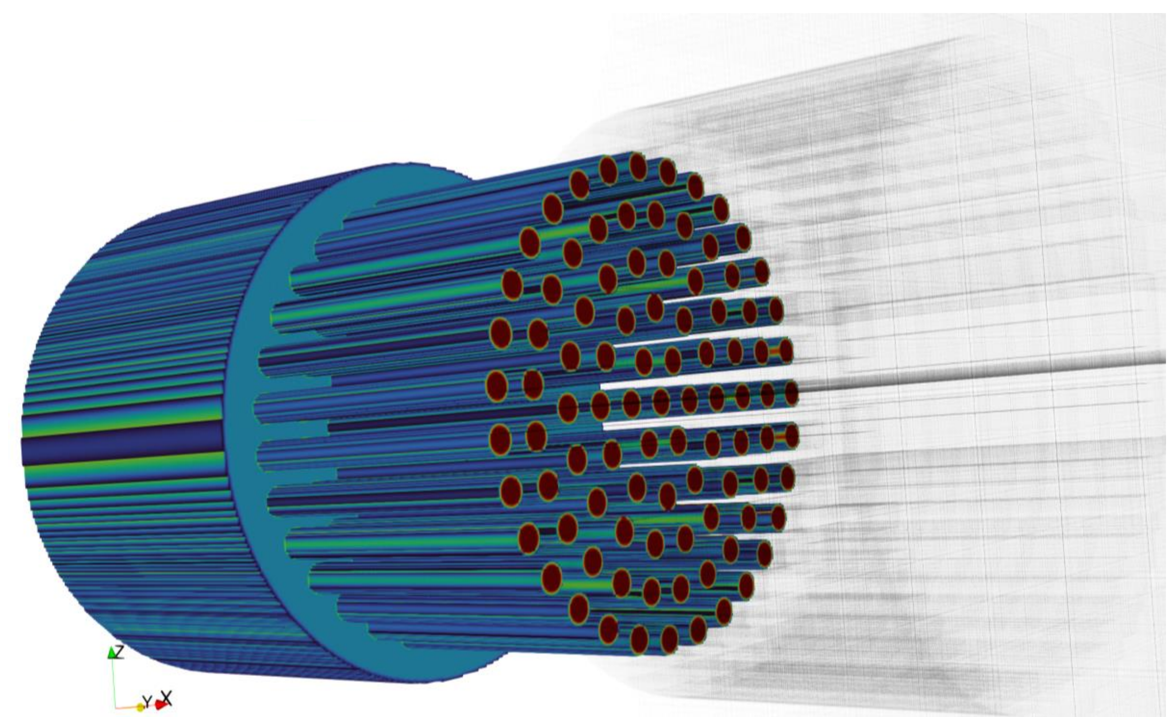
Project Objectives:

- Objective 1 – use hierarchy of experiments/laser diagnostics to quantify rate-limiting physics; what physics need to be captured in models?
- Objective 2 – develop suite of validated, multi-regime computational models
- Objective 3 – characterize operability and operational limits (exploration of parameter space) for burner and AFS systems




*Simulation of flashback along a centerbody in swirling flow using LES*



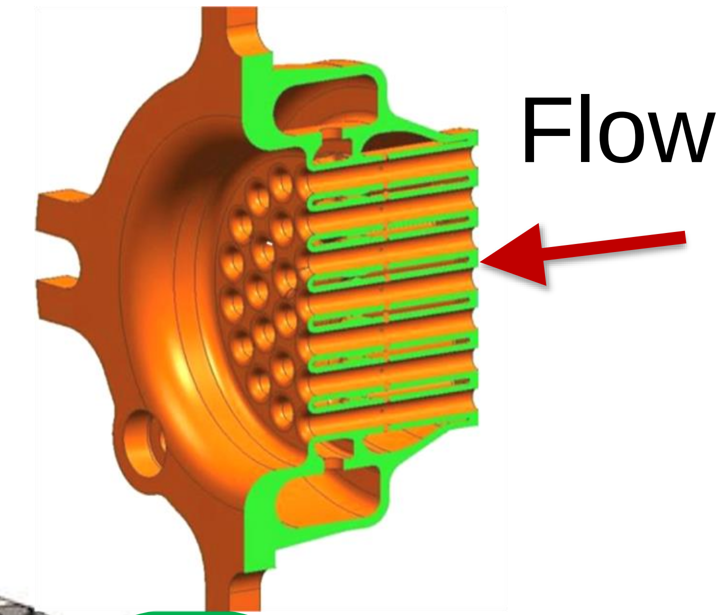



*DNS of full-scale micromixer (discussed later by V. Sharma)*

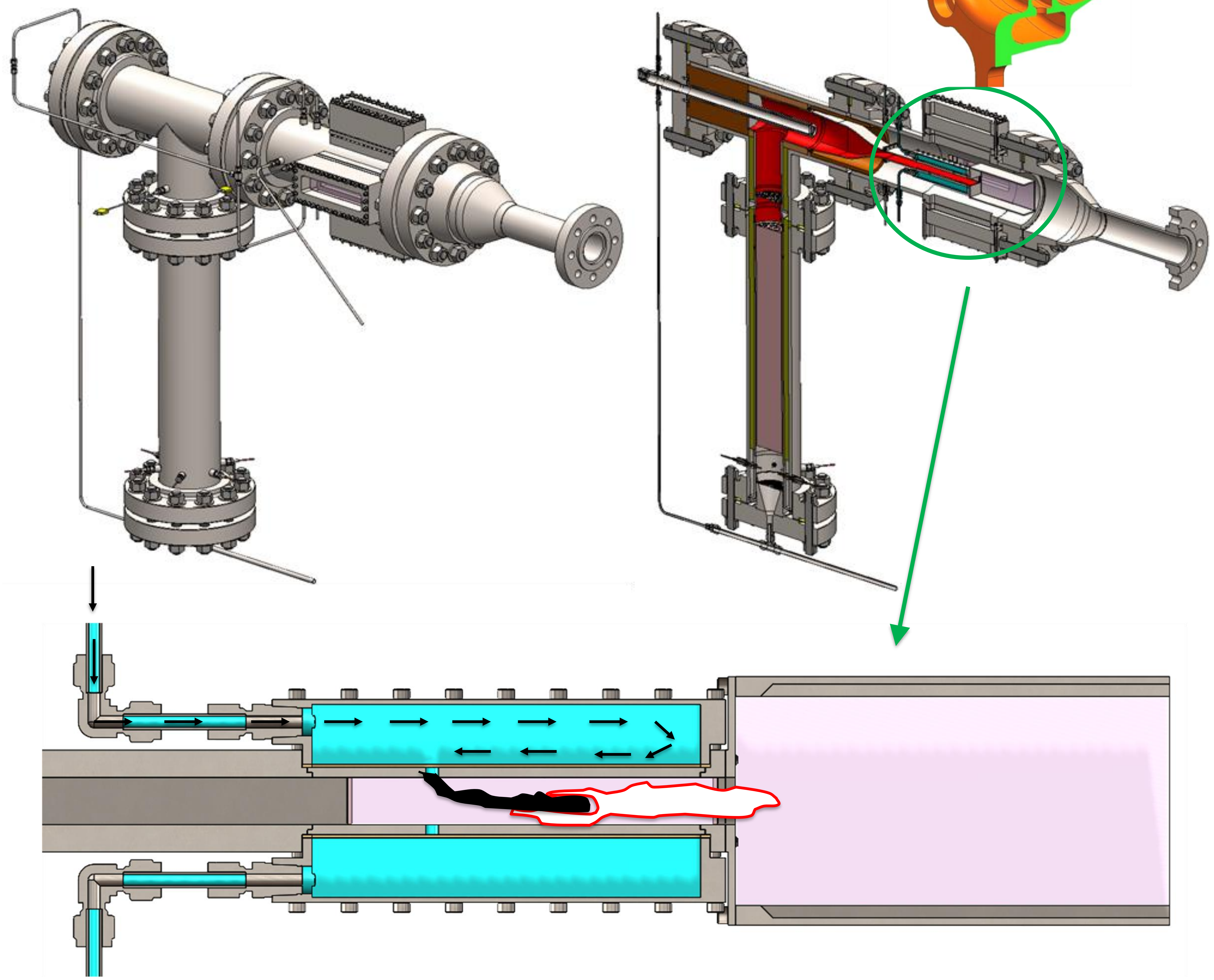
# Design of Experimental Test Conditions

## Goals:

- Configurations and test conditions model important flow and geometric features under engine-relevant conditions
- NOT a duplication – captures key features that should be modeled for flameholding and flashback

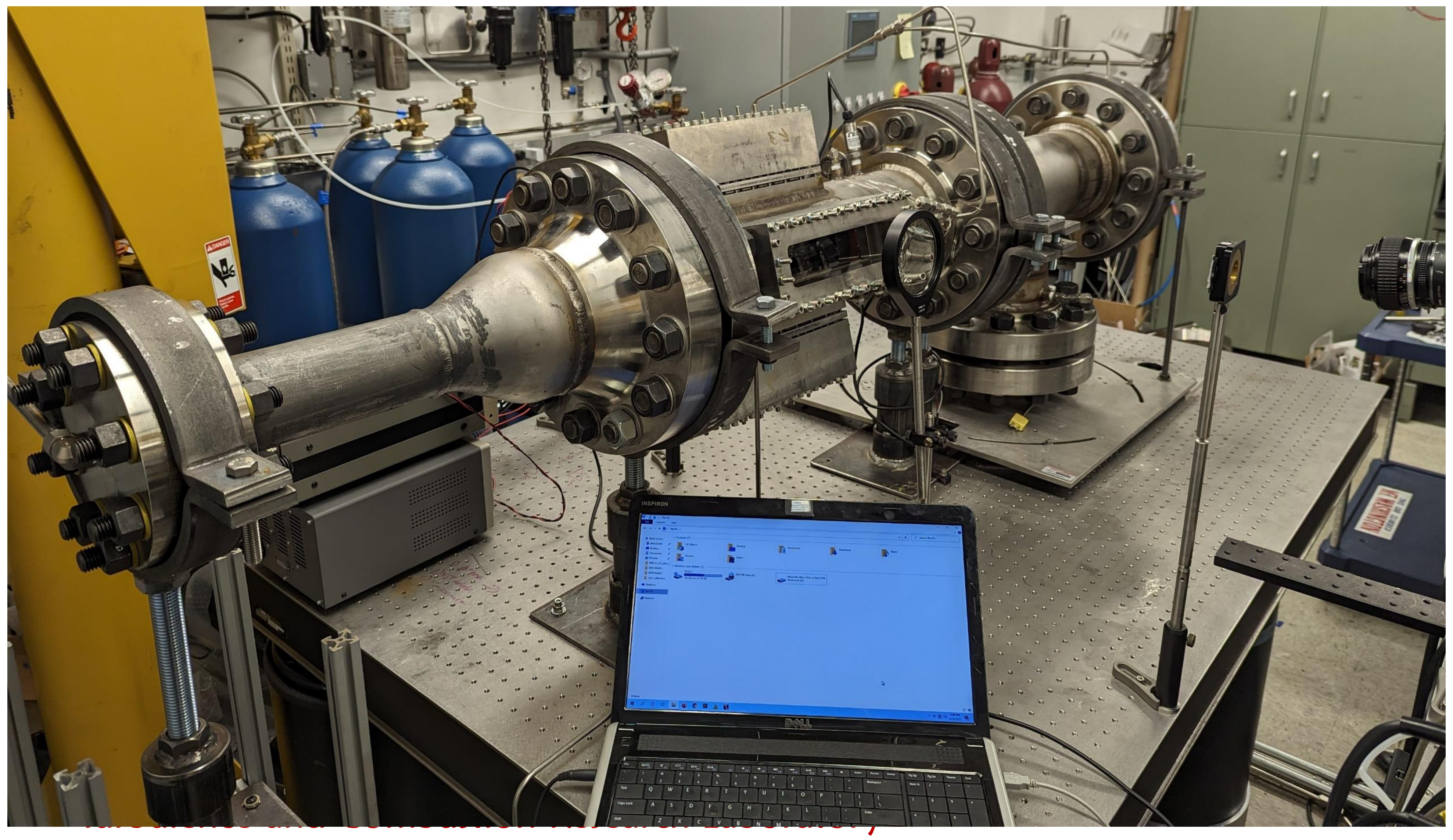


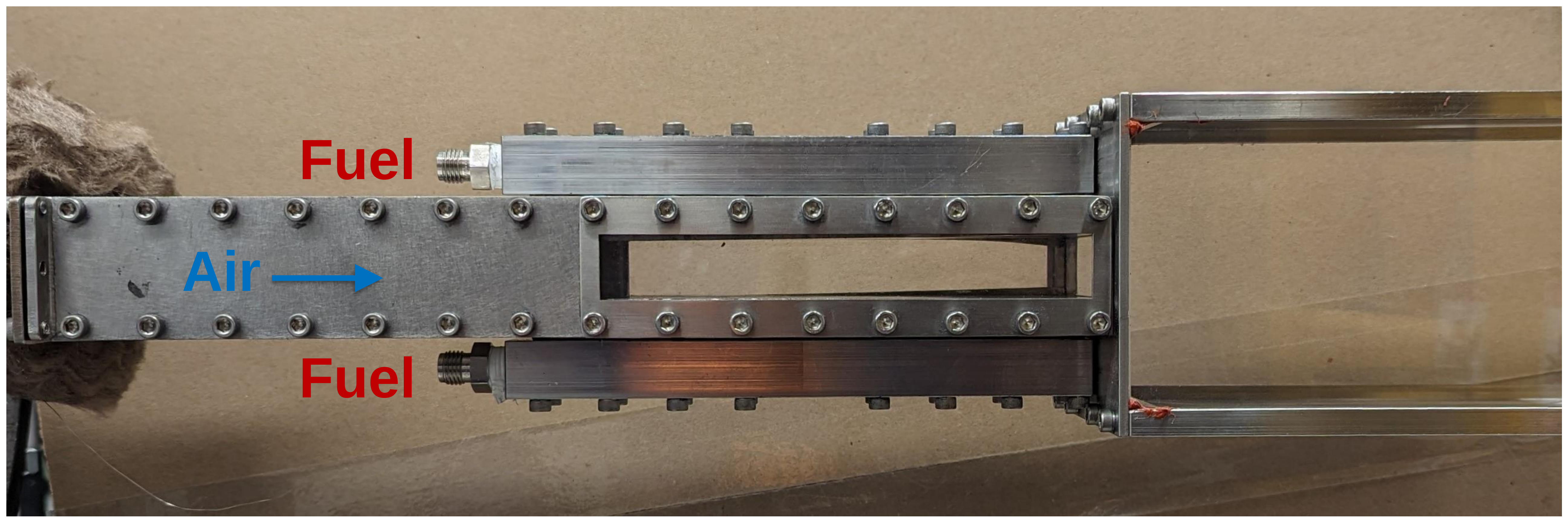

| | SEPB 1 | SEPB 2 | SEPB 3 | SEPB 4 |
|---|---|---|---|---|
| Air tube ID / channel H x W (inch) | 0.75 x 3 | 0.75 x 3 | 0.75 x 3 | 0.75 x 3 |
| Fuel hole D (inch) | 0.205 | 0.205 | 0.205 | 0.205 |
| Number of fuel holes | 2 | | | |
| Fuel hole angle (deg) | 0 | | | |
| Pressure (bar) | **17.2** | **8.0** | **4.0** | **1.0** |
| Inlet air temperature (K) | 670 | | | |
| Inlet air velocity (m/s) | 2.51 | 5.41 | 10.80 | 43.30 |
| Inlet air Re ( based on channel height) | 23400 | 23400 | 23400 | 23600 |
| Air mass flow rate (slpm) | 1510 | 1510 | 1510 | 1530 |
| Heat addition to air (kW) | 13.0 | 13.0 | 13.0 | 13.1 |
| Fuel composition (% vol) | 40/60 $CH_4/H_2$ | | | |
| Inlet fuel temperature (K) | 590 | 590 | 590 | 590 |
| Inlet fuel velocity (m/s) | 7.47 | 16.10 | 32.10 | 128.00 |
| Inlet fuel Re | 9390 | 9390 | 9390 | 9480 |
| Total fuel mass flow rate (slpm) | 150 | 150 | 150 | 152 |
| Flame power (kW) | 52.0 | 52.0 | 52.0 | 52.5 |
| Fuel/air momentum ratio | 2.64 | | | |
| Fuel/air mass flow rate ratio | 0.026 | | | |



# Test Rig Construction

- A number of delays that impacted construction
  - Initial fabrication of many parts were delayed by 3+ months
  - Many major/minor parts had to be fabricated twice due to machinist error
  - Personnel issues – new postdocs only started July 2023 (1-year gap between staff)
  - University halted work with an existential crisis about hydrogen and its usage
- Test rig has now been assembled
- System control (temperature, pressure, flow rates, etc) has been installed and tested






**Burner Assembly**

# Test Rig Construction

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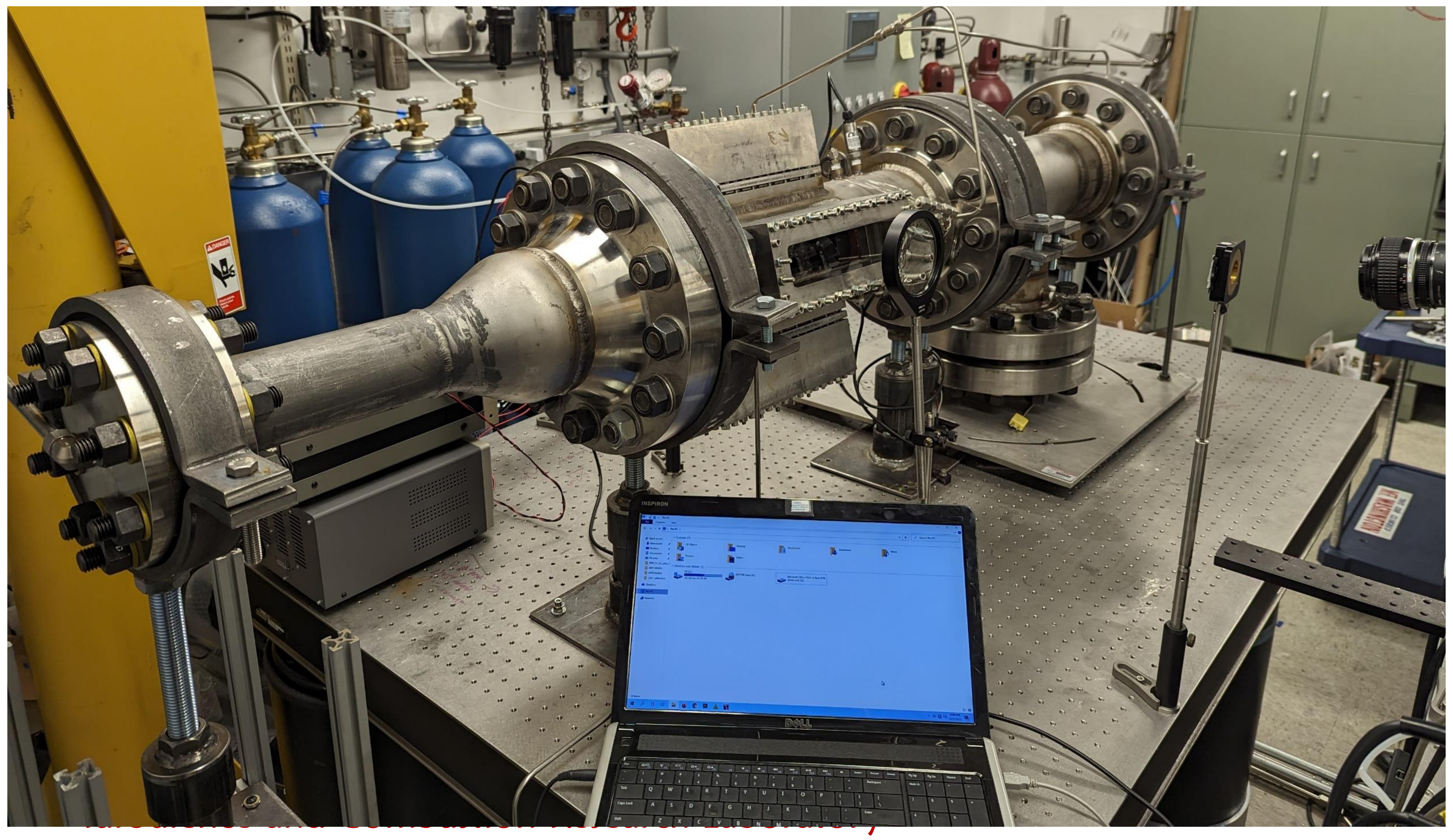
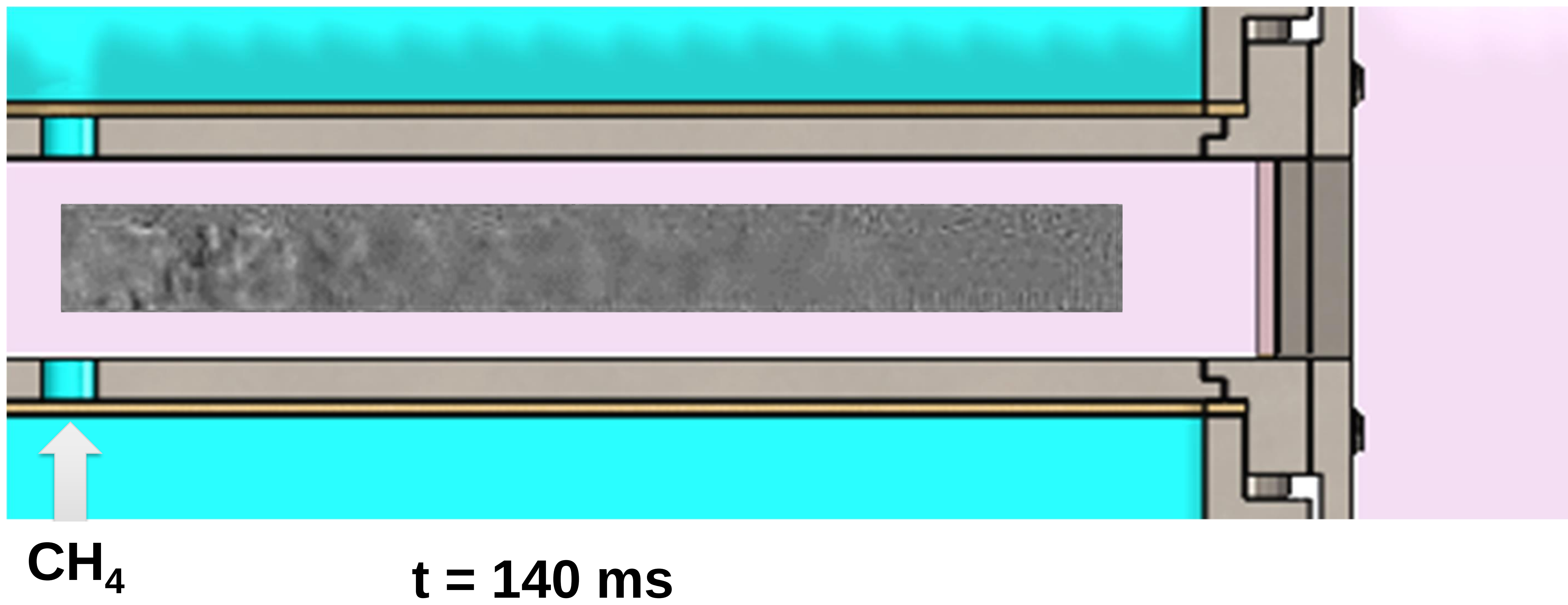
- Test rig has now been assembled
- System control (temperature, pressure, flow rates, etc) has been installed and tested
- Facility shakedown has begun (atmospheric and pressurized cold flow cases)





- During system fabrication and construction, we have optimized laser-based measurements

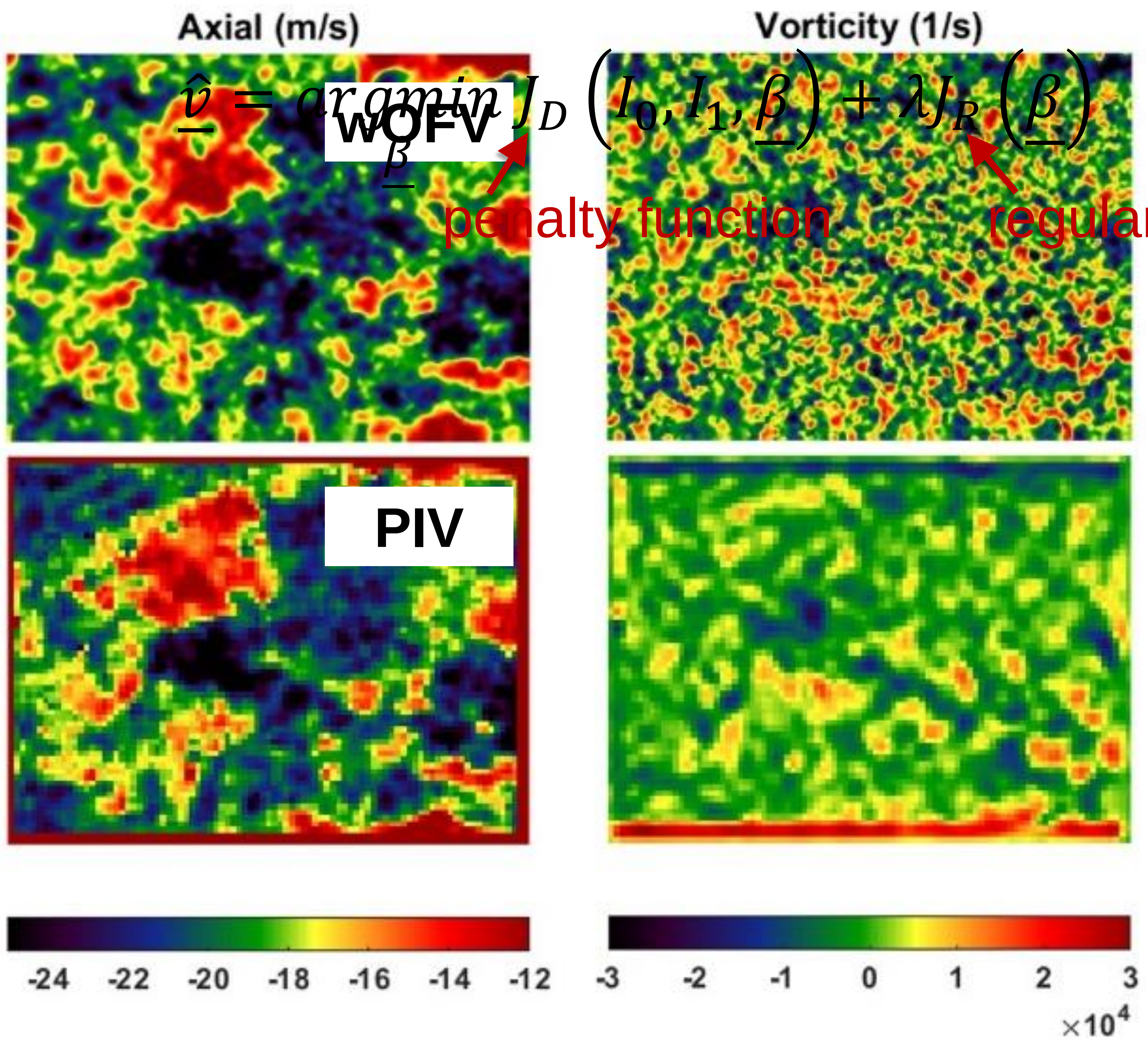
DLR turbulent premixed burner (5 bar)

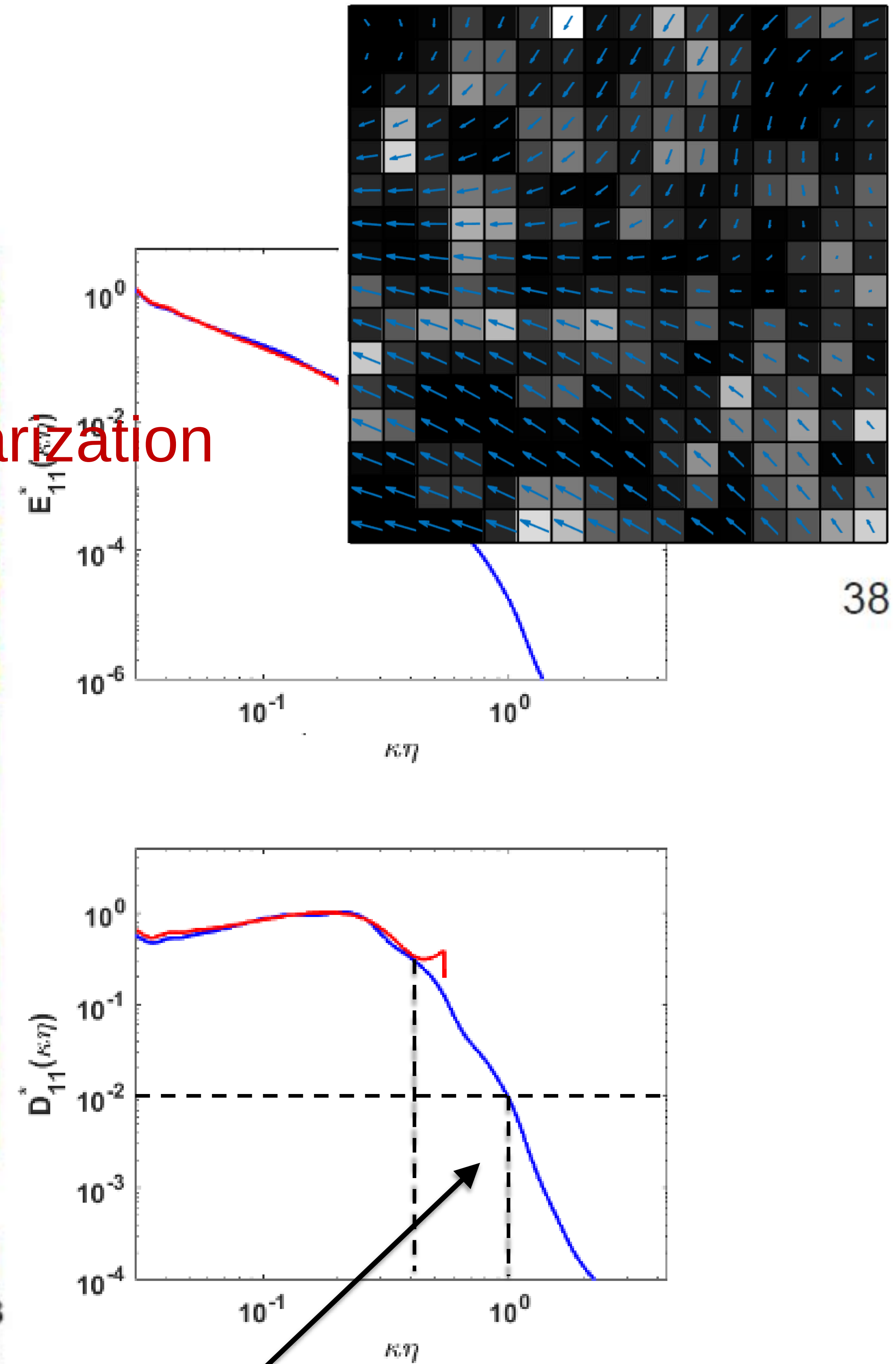
$I_0(x,t) = I_1(x + v(x)t) + O(\cdot)$

**Flow direction**

$\hat{v} = \arg\min_{\beta} J_D(I_0, I_1, \beta) + \lambda J_R(\beta)$

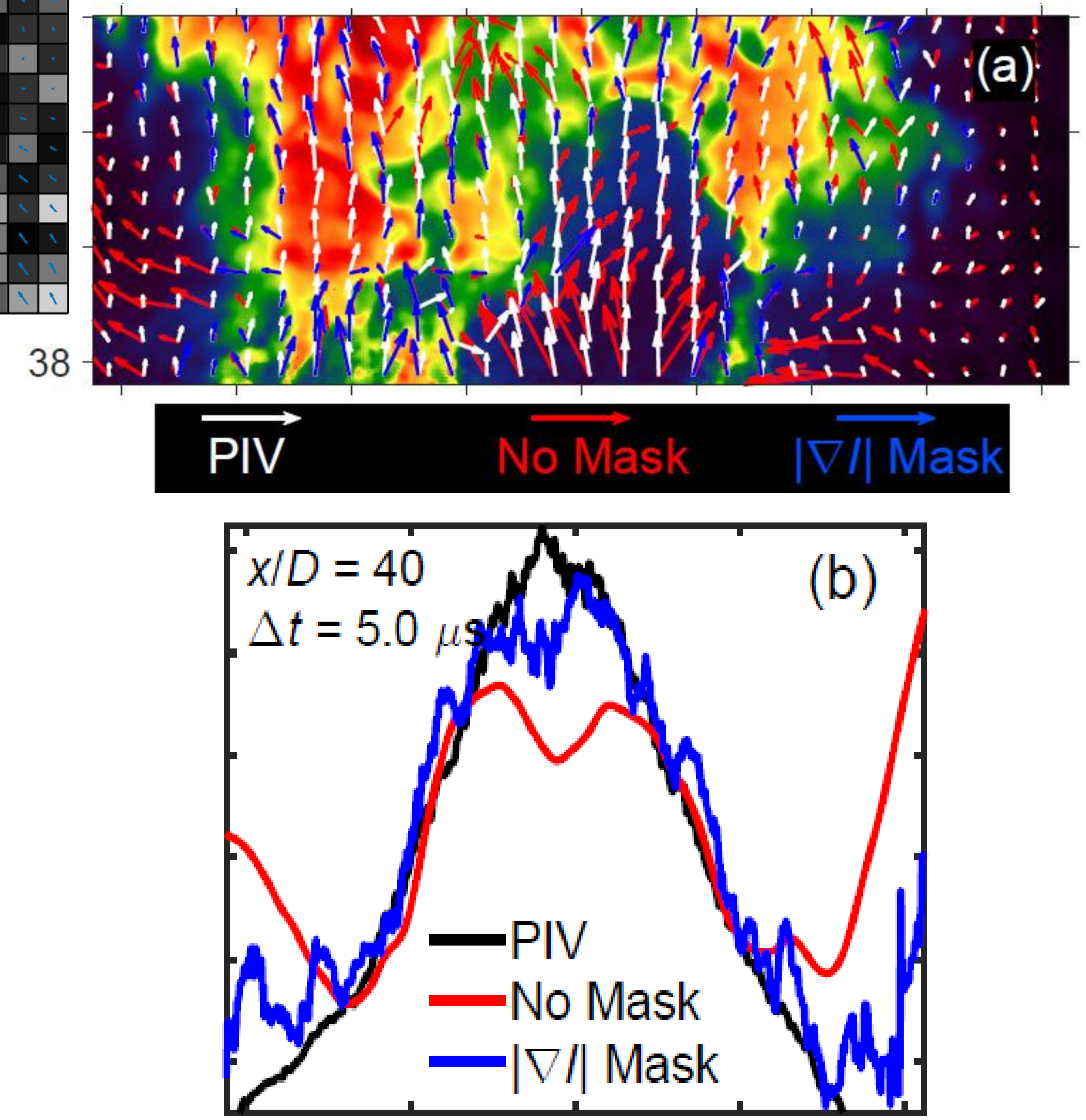
penalty function — regularization



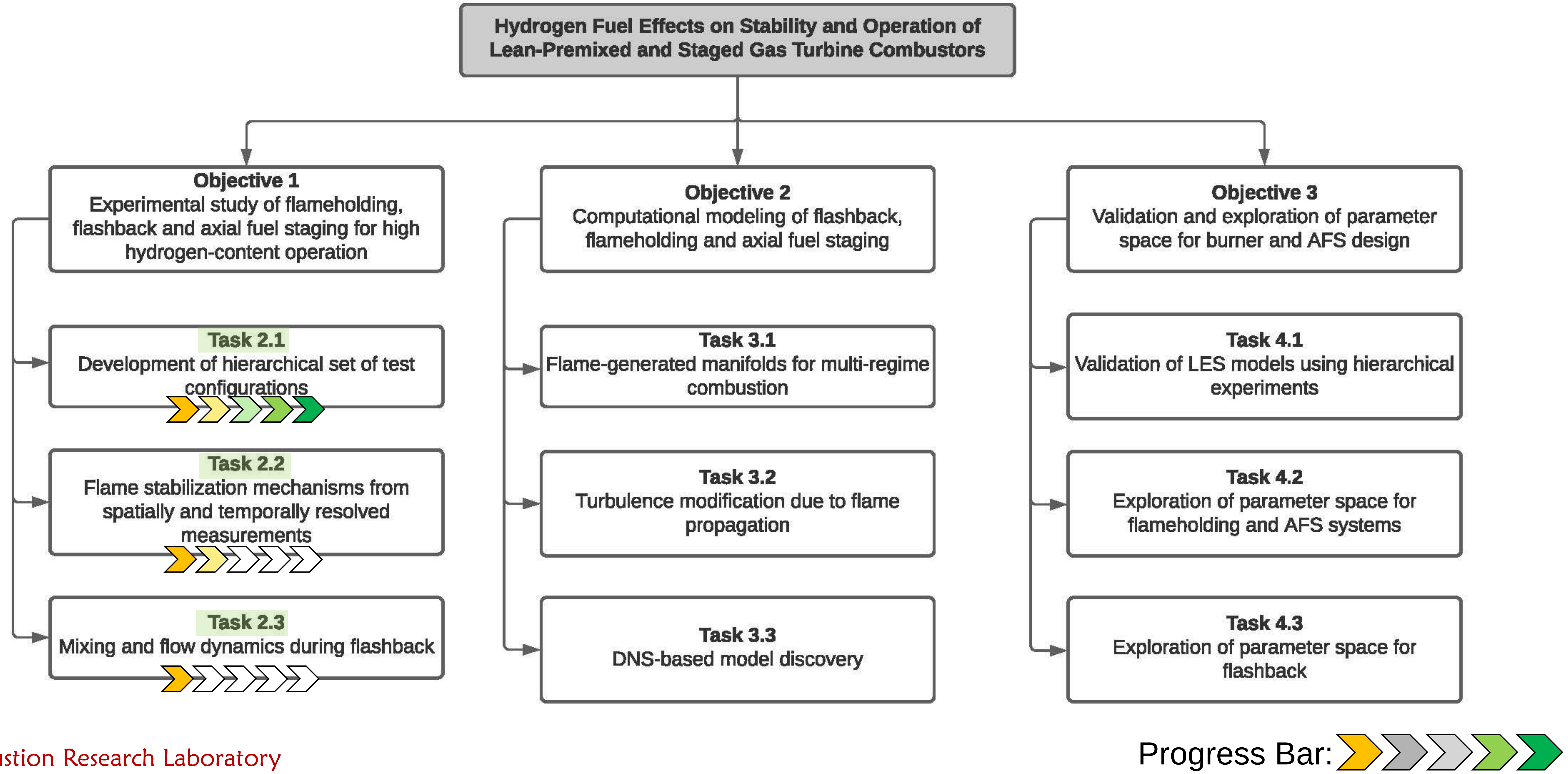

**Smallest dissipative scales resolved**

**Dual-Shot OH PLIF + wOFV**



# Experimental Status and What's Coming…

- Test rig is setup; in the final year of this program, data will be acquired, analyzed, and passed to UM collaborators for LES model assessment (focus is on stabilization and flameholding mechanisms)
- The experimental testbed provides new opportunities for identifying mechanisms underpinning flameholding, stabilization, and flashback when using HHC fuels
- Longer term - testbed scale is ideal for "rapid" parametric evaluation of HHC combustion – fundamental mechanisms



# DOE-NETL USTR Program Review Meeting

**FE0032076 -** Hydrogen Fuel Effects on Stability and Operation of Lean-Premixed and Staged Gas Turbine Combustors

## Computational Effort

30 - Oct - 2023


Co-PI: Venkat Raman

Presenter: Vansh Sharma

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# Overview

A. LES Studies

B. DNS Studies

C. Flashback Studies

Focus: core flow physics and flame processes that control combustor operation using hydrogen and hydrogen-containing (HC) fuels

**Develop framework** for understanding following limit processes:

- Flame-holding
- Flame blowout
- Flashback

Processes are combination of different phenomena

- Entrainment
- Strain Rate – Extinction with chemistry effects
- Turbulent boundary layer
- Heat transfer effects

LES: Large-Eddy Simulation; DNS: Direct Numerical Simulation

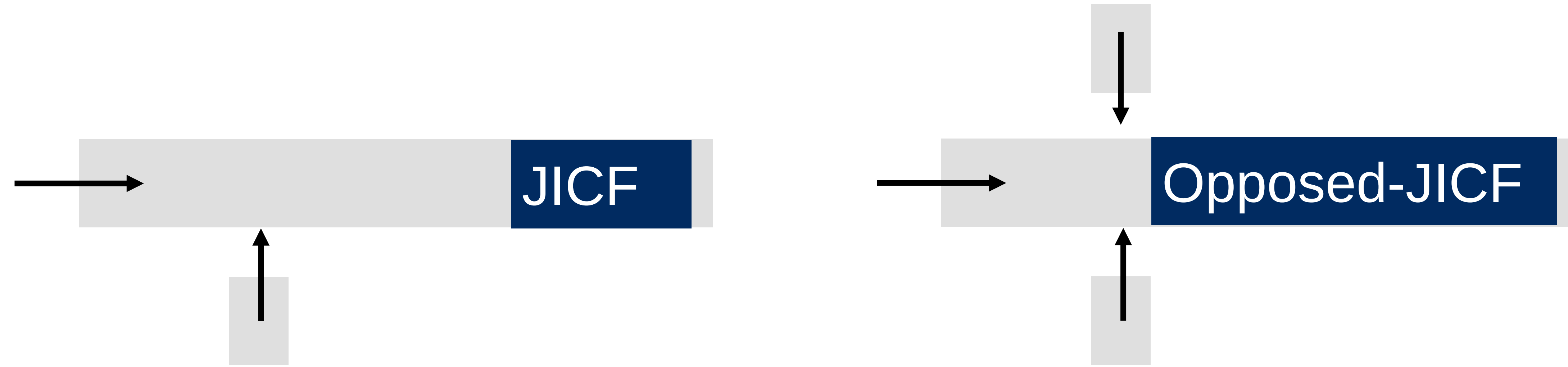
# Overview

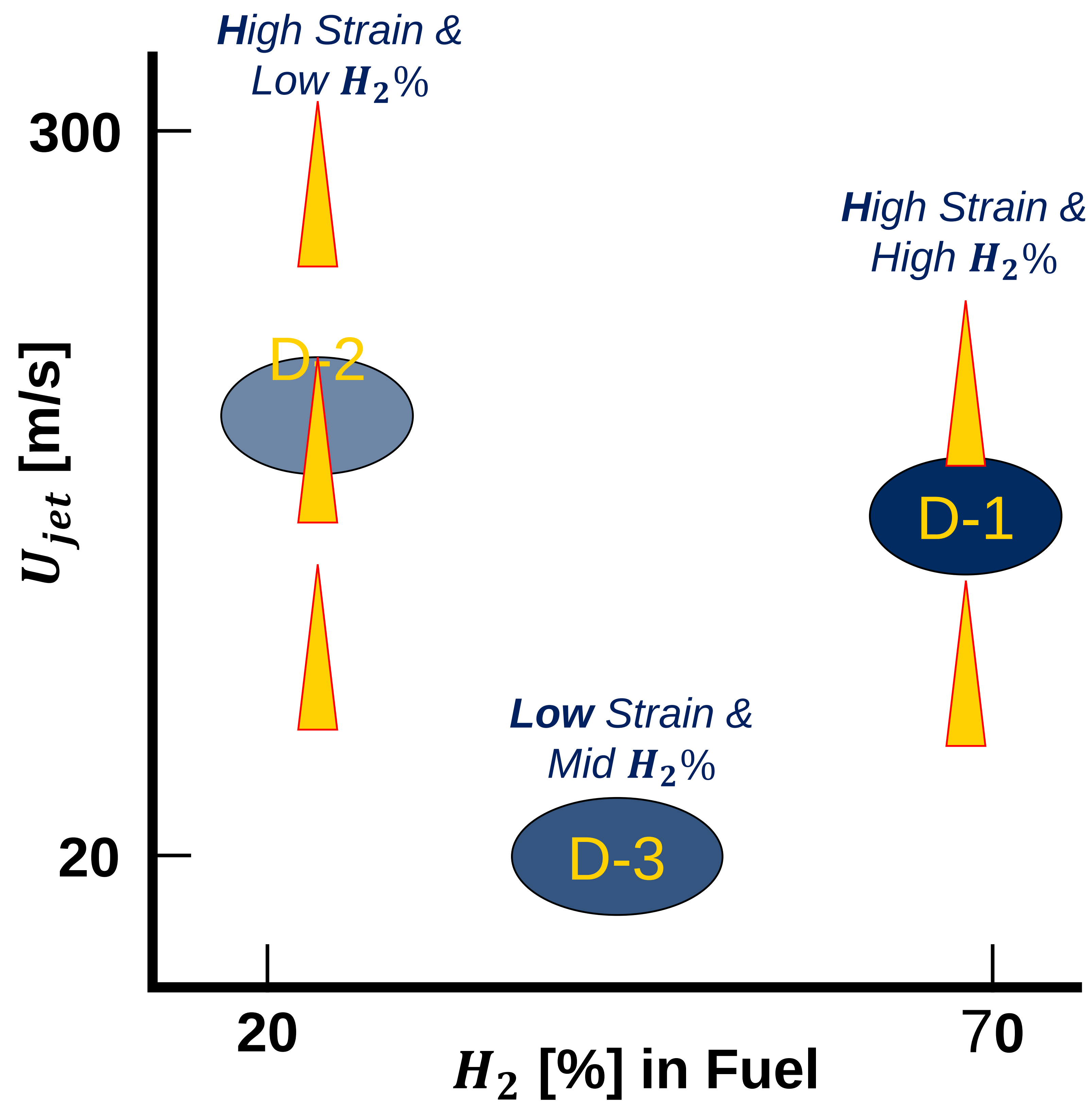
A. LES Studies

DNS Studies

Flashback Studies

- Understand the flame behavior in a representative geometry - JICF
  - Flamelet-based combustion modeling
- Model validation via experiments
  - Combustion model limits: Non-Premixed vs Premixed Tabulation
- Cases from literature [1]-[3]
  - Bounds of strain rate vs Hydrogen %
  - Flame stabilization and blowout process




D1: Steinberg et. al - https://doi.org/10.1016/j.proci.2012.06.026

D2: Steinberg et. al - https://doi.org/10.1016/j.proci.2012.05.039

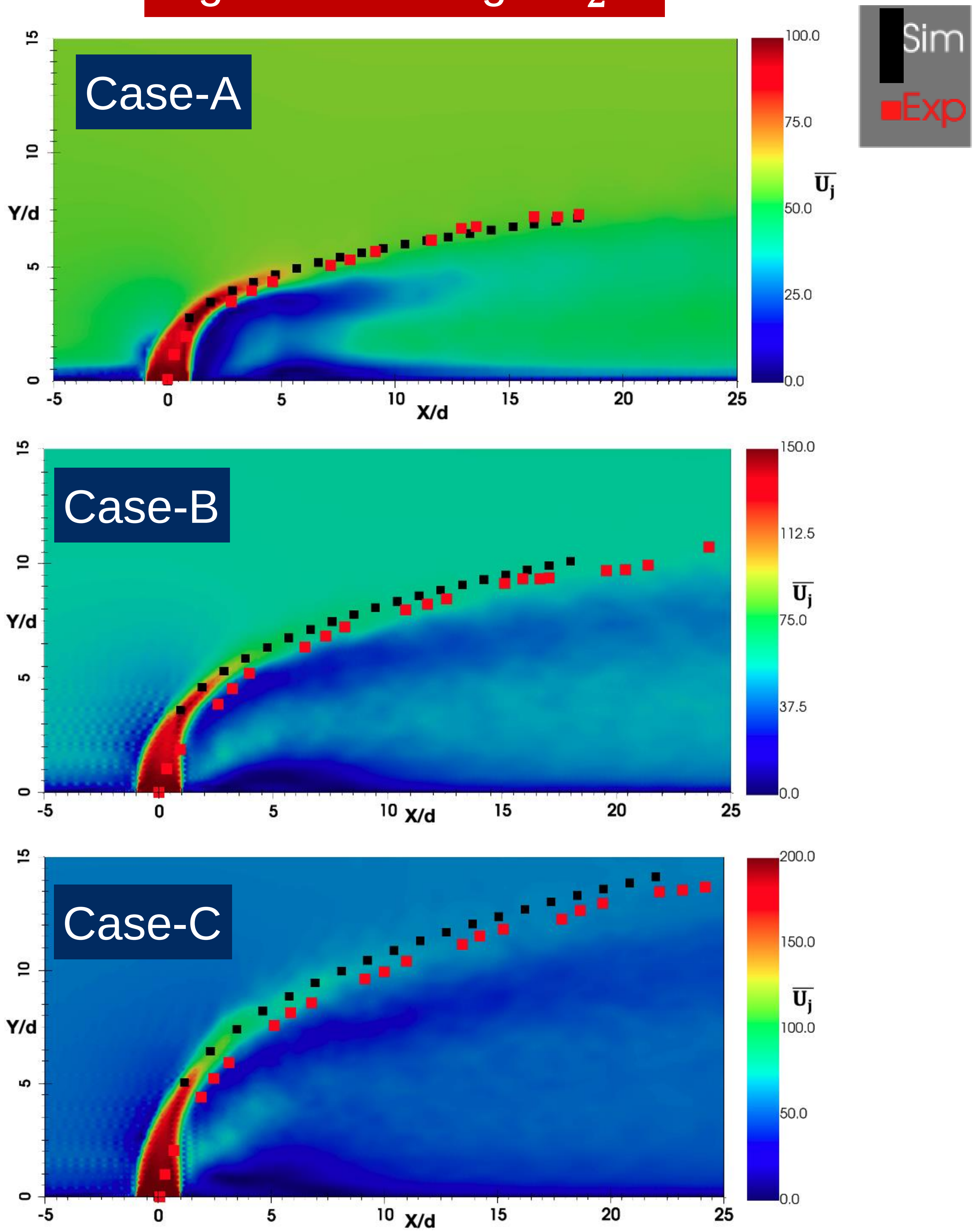
D3: Aigner et al. - https://doi.org/10.1007/s10494-020-00148-8

Plot axis not to scale

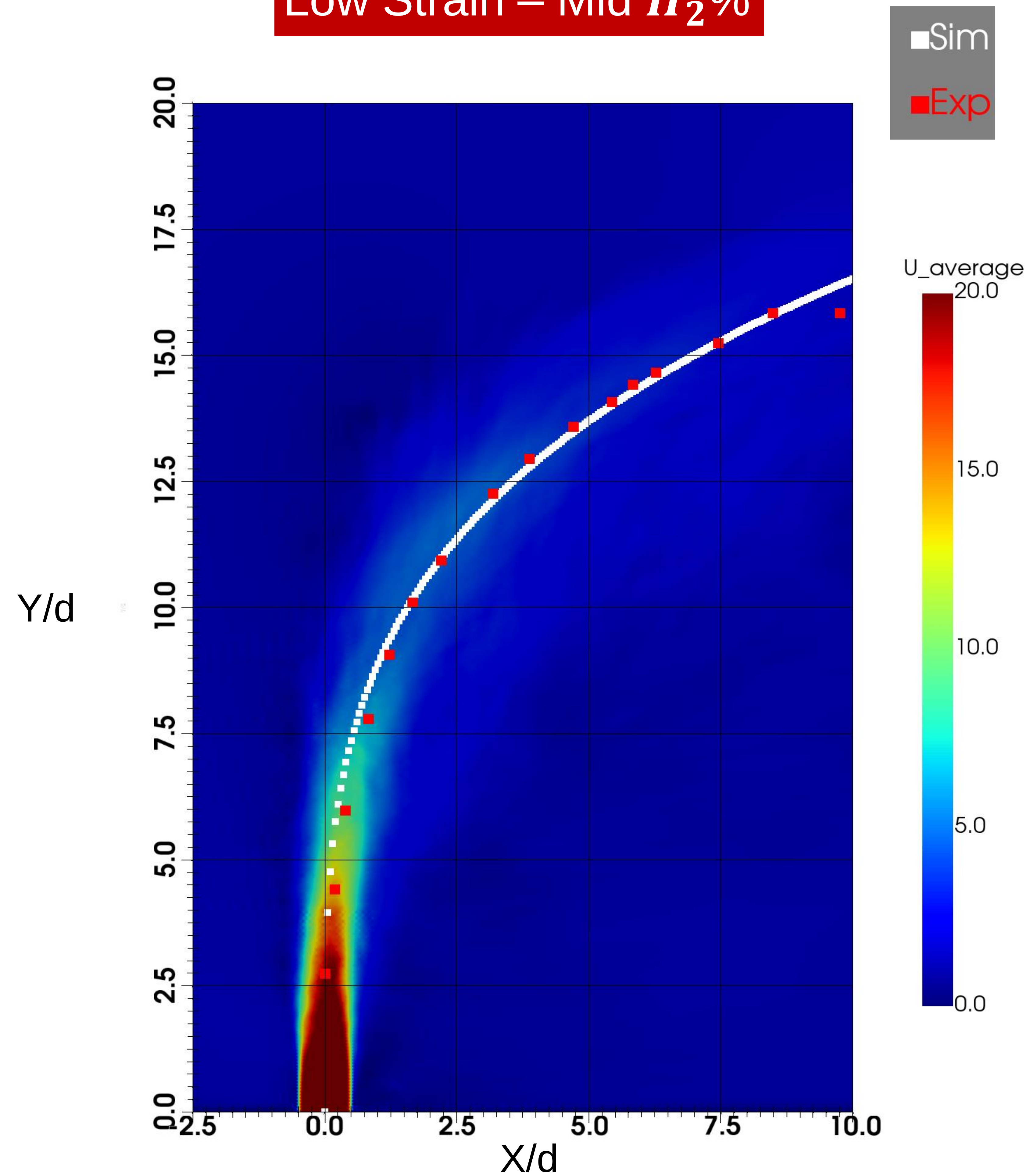
LES: Large-Eddy Simulation; JICF: Jet in Crossflow

# JICF Studies: Key Results

High Strain – High $H_2\%$




Low Strain – Mid $H_2\%$




V. Sharma, Y. Tang and V. Raman. Stabilization of Hydrogen-enriched Jet Flames in a Crossflow [accepted to AIAA SCITECH 2024 Forum]

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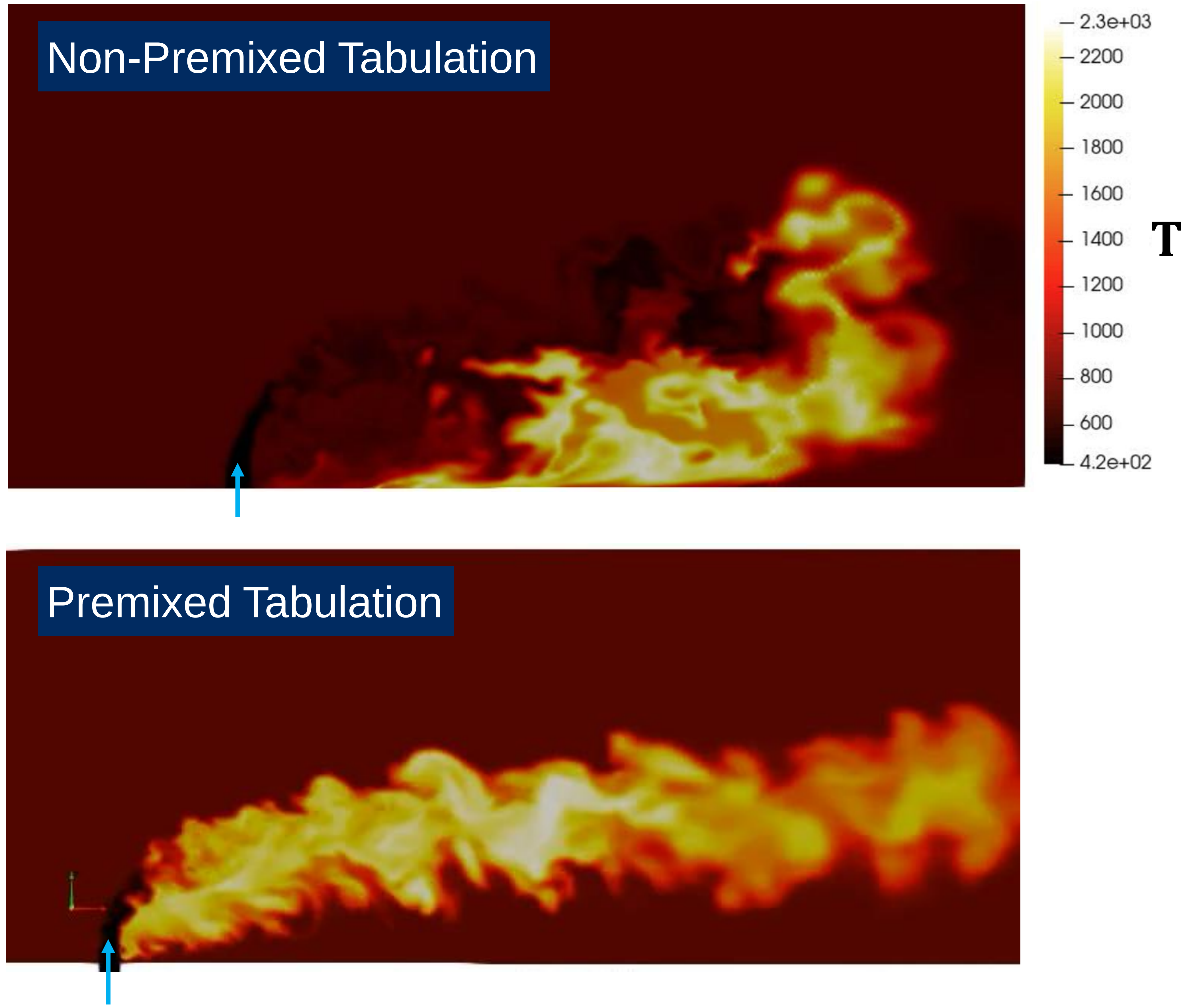


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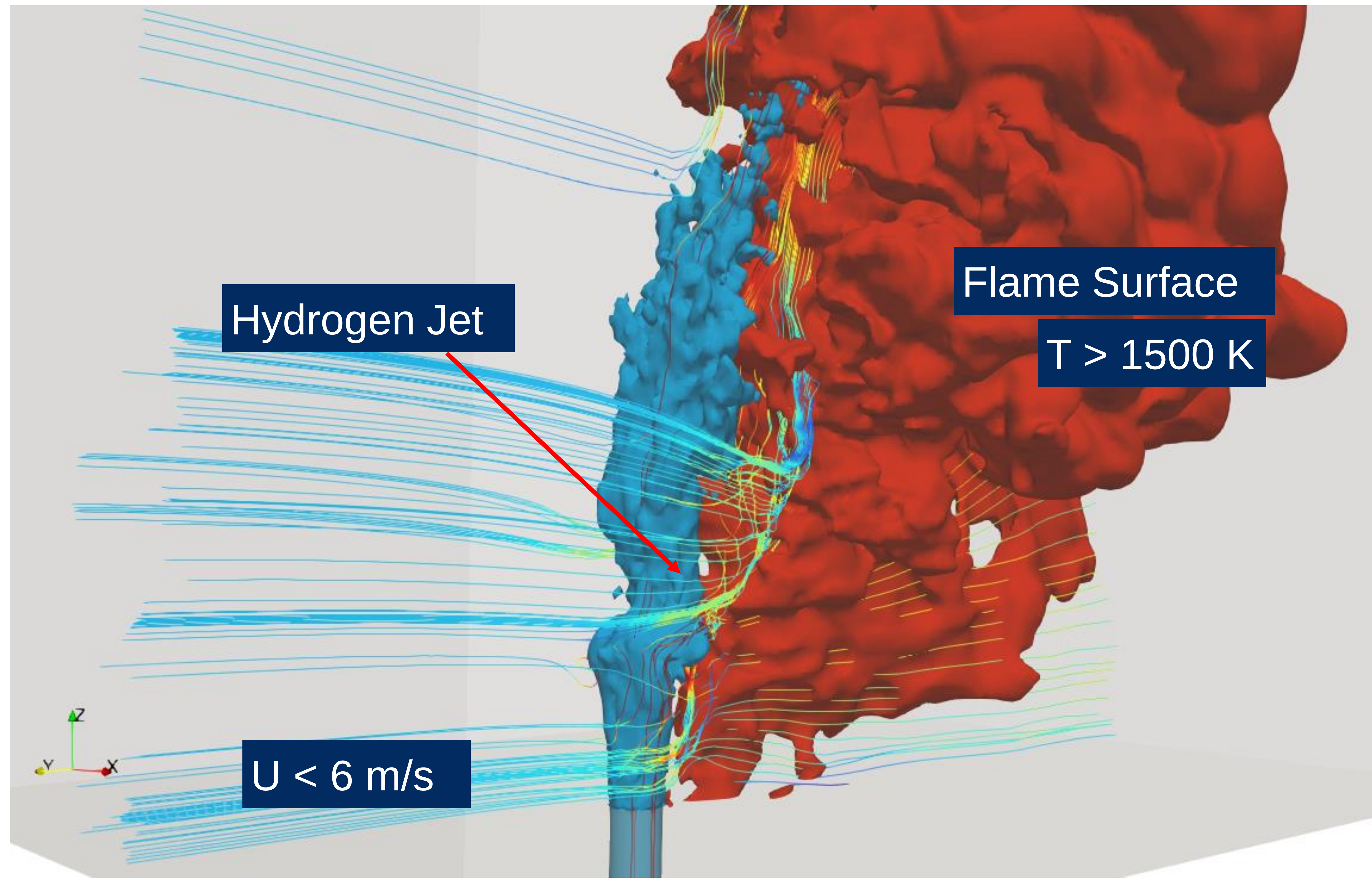


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# Overview

B. DNS Studies

Flashback Studies

JICF Studies

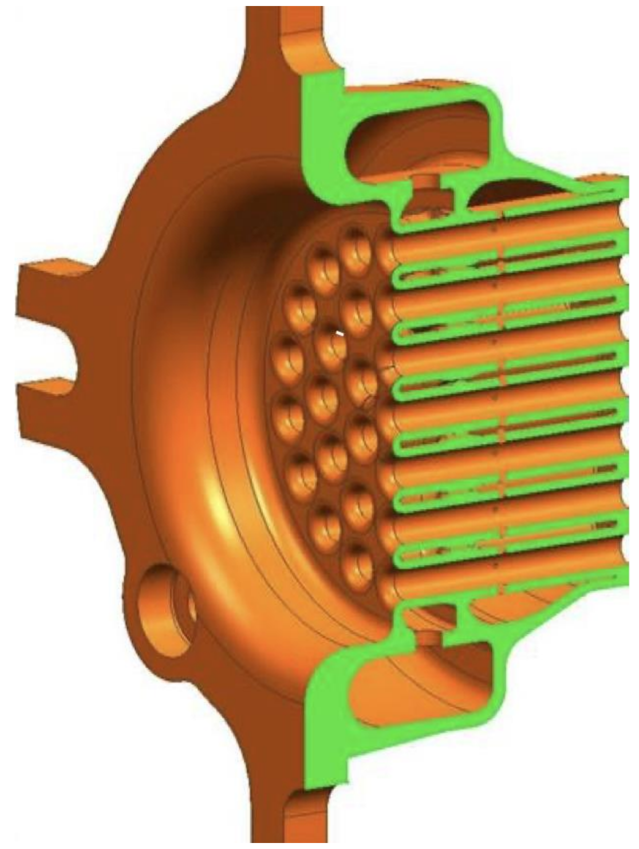
In collaboration with GE [Michael Hughes and Hasan Karim]

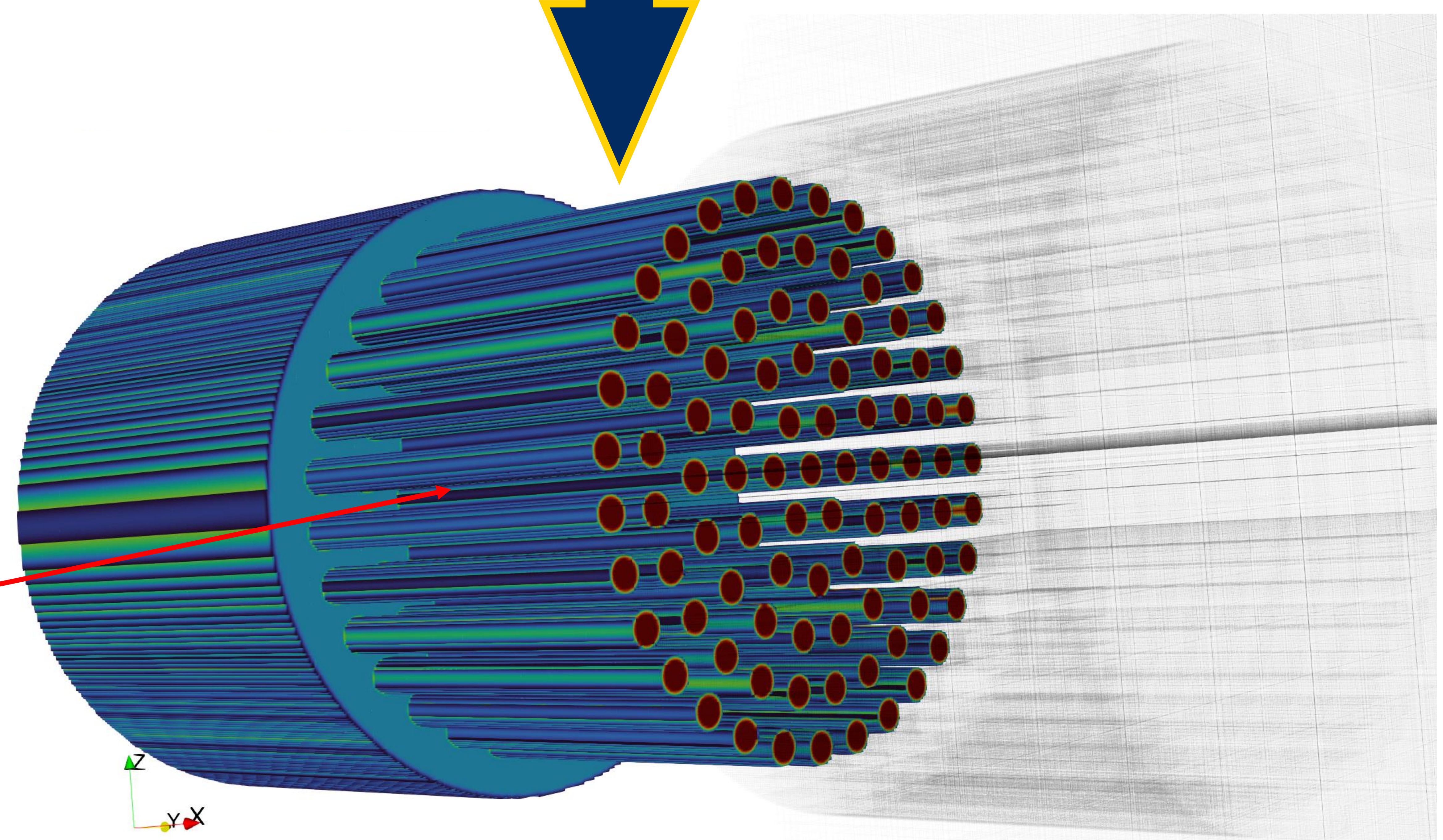
Adaptive Mesh Refinement [AMR] based solver with full chemistry implementation using Cantera and/or in-house Chemistry Lib

Solver Capabilities

- AMReX [5] based – Exa-Scale ready
- Mesh refinement + Field Refinement control
- Finite Rate chemistry scalable on GPUs [4]

Multi-Tube Mixer (MTM)

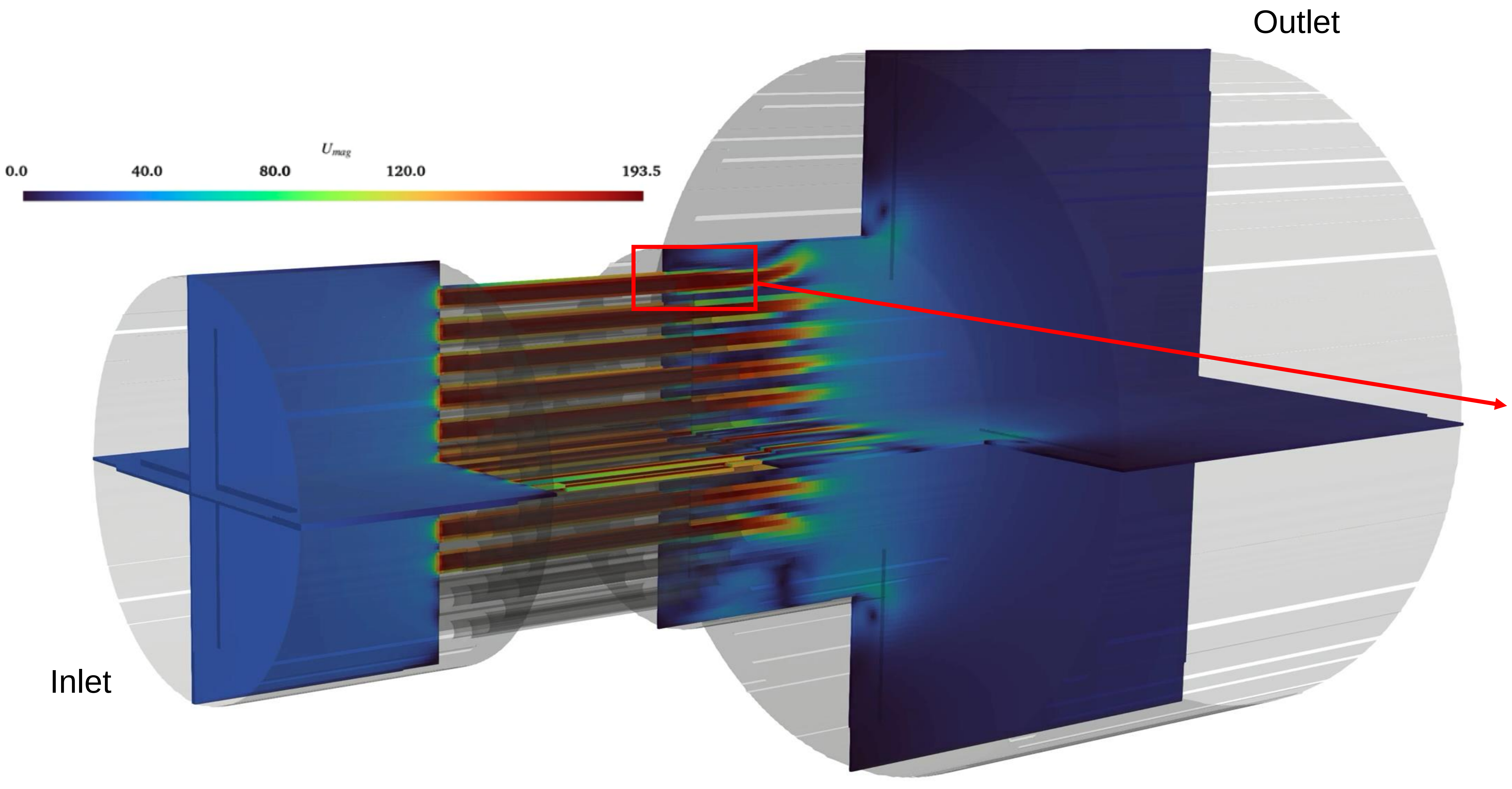


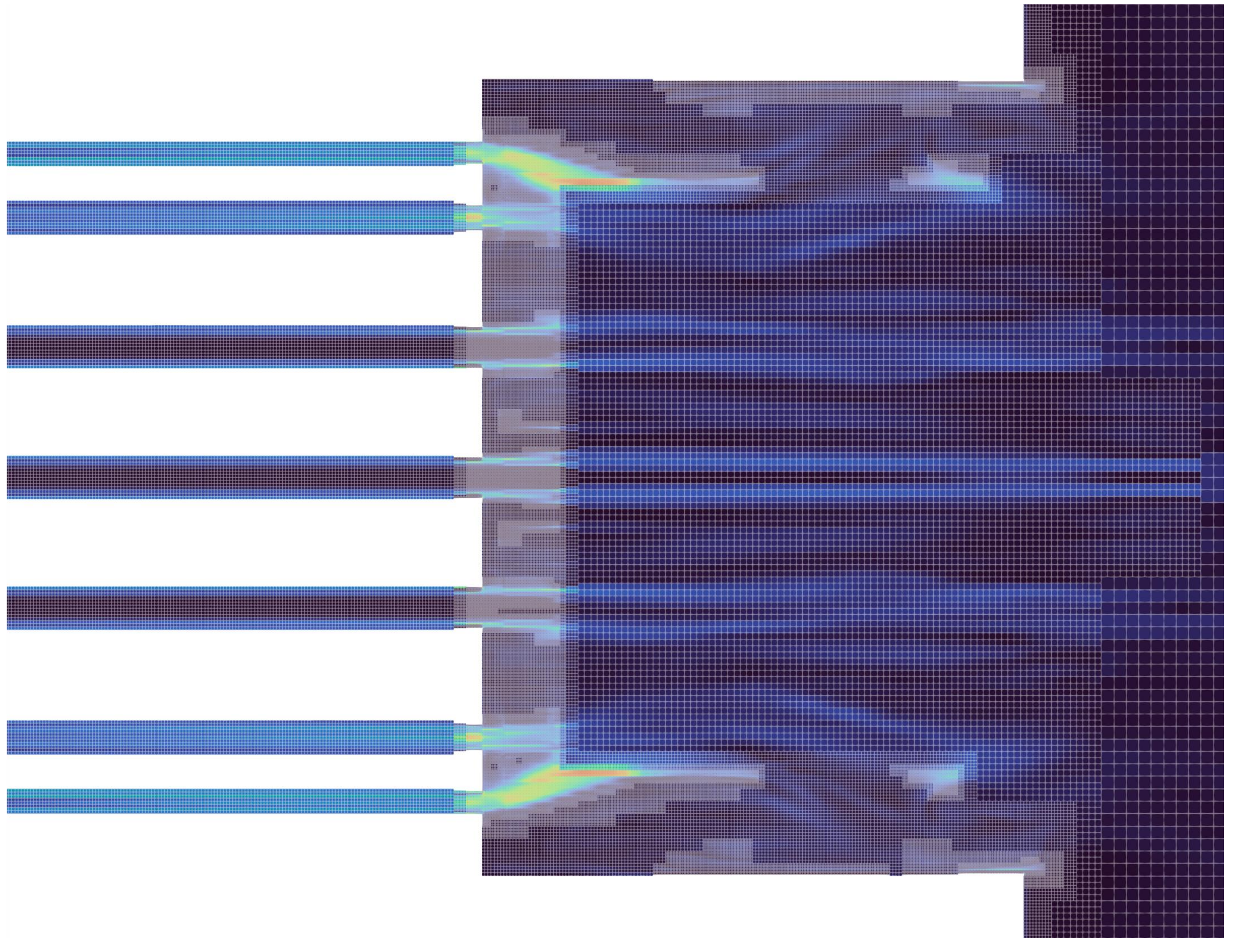



Tubes meshed using Implicit Function – Faster and Precise Mesh

DNS: Direct Numerical Simulation

# DNS Studies: In Progress



Section View showing tube exit with vorticity refinement



Sharma, V.

# Overview

APCL

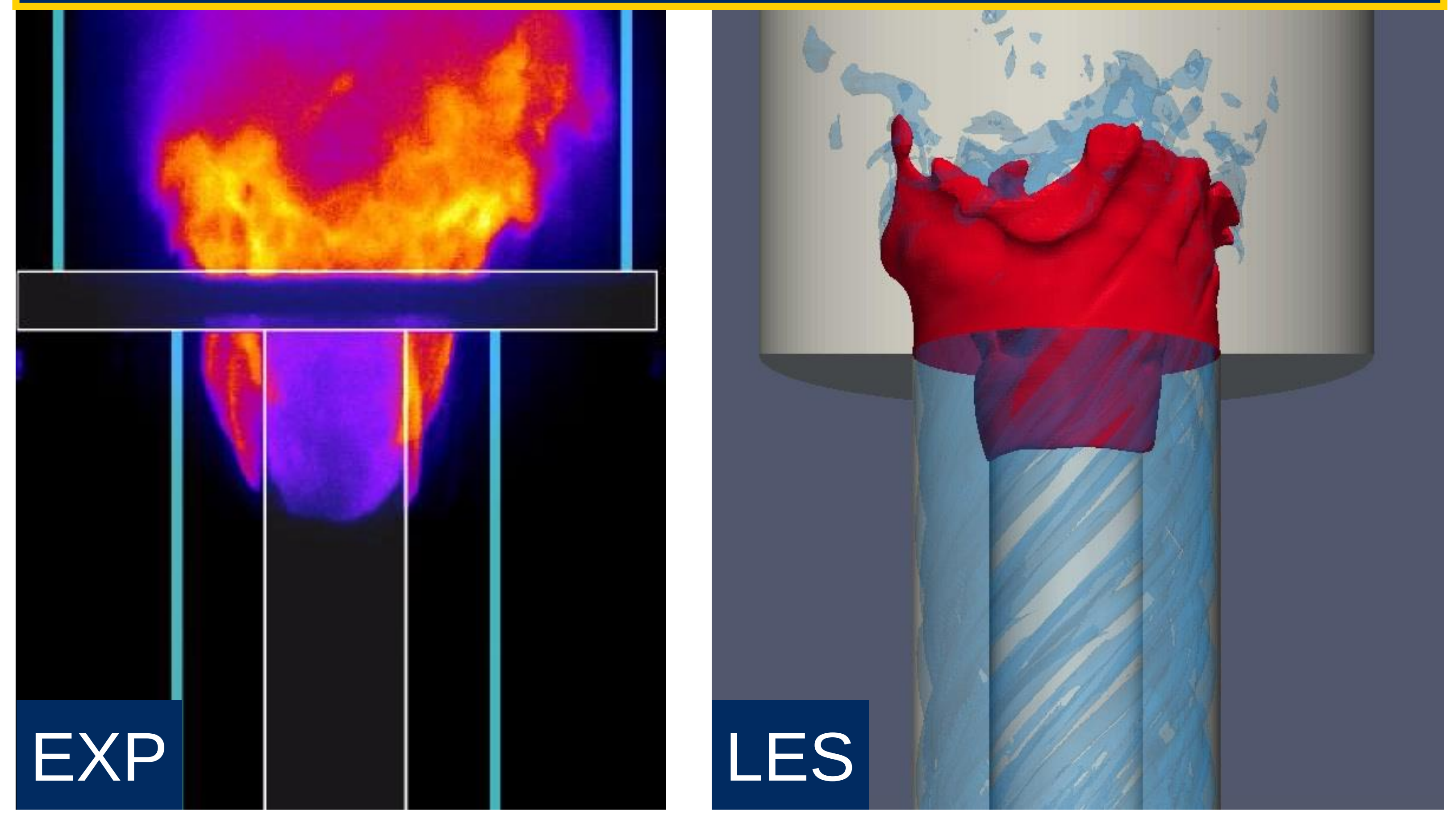
## C. Flashback Studies

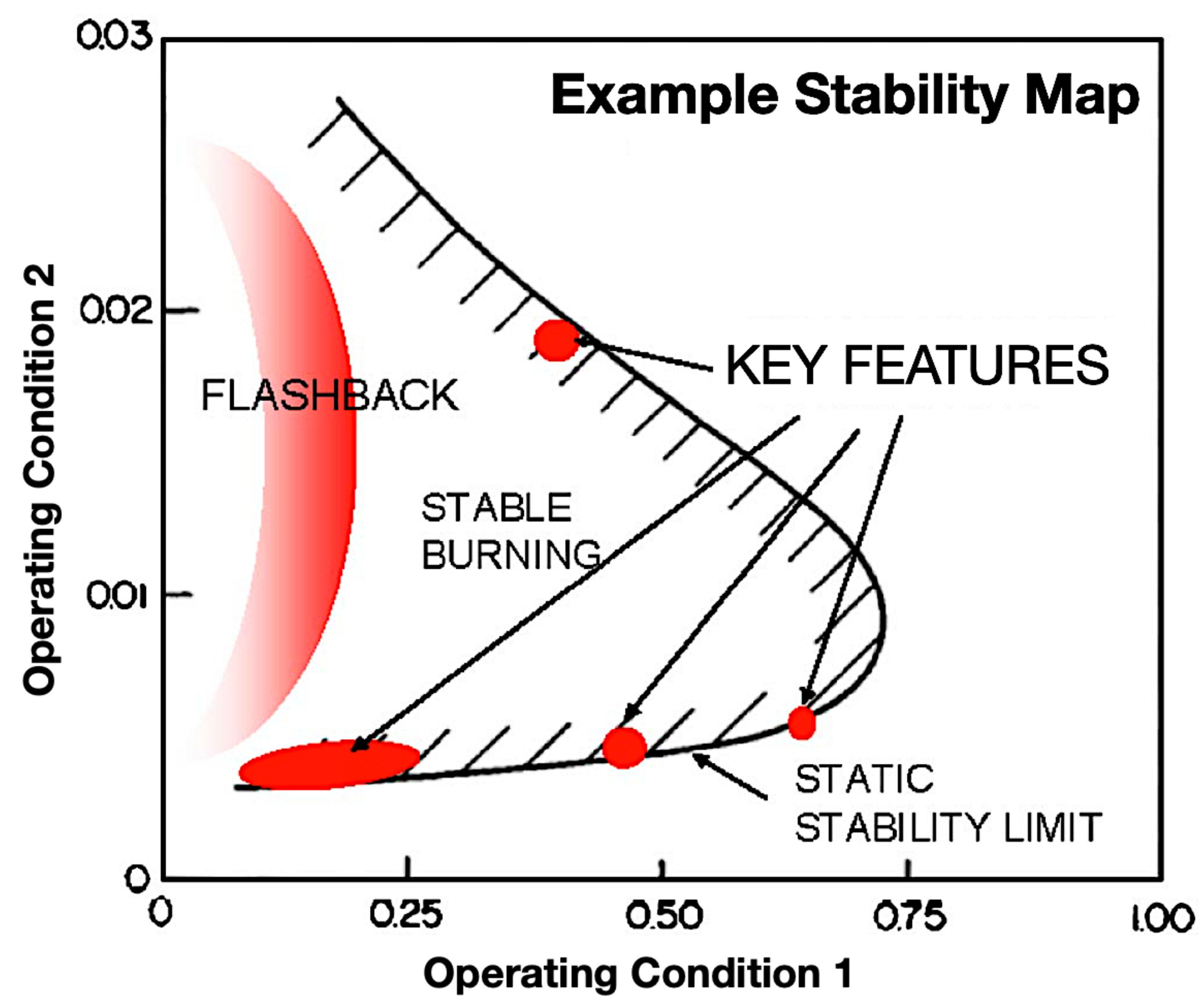
- Complicated – different unsteady processes involved
  - Boundary layer (BL) flashback dominates in $H_2$ fuels
- Previous work in UTSR project
  - BL Flashback in Swirl combustor
  - Direct dependence on – Turbulent BL, Heat Transfer and Chemistry
- Develop models for flashback using LES and DNS data
  - Open to combustion community: LES Models and DNS data

JICF Studies

DNS Studies

**LES Modeling and Experiments of Flashback in $H_2$ Rich Gas Turbines: Raman & Clemens**



# Summary: Tasks

**Hydrogen Fuel Effects on Stability and Operation of Lean-Premixed and Staged Gas Turbine Combustors**

**Objective 1**
Experimental study of flameholding, flashback and axial fuel staging for high hydrogen-content operation

- **Task 2.1**
  Development of hierarchical set of test configurations
- **Task 2.2**
  Flame stabilization mechanisms from spatially and temporally resolved measurements
- **Task 2.3**
  Mixing and flow dynamics during flashback

**Objective 2**
Computational modeling of flashback, flameholding and axial fuel staging

- **Task 3.1**
  Flame-generated manifolds for multi-regime combustion
- **Task 3.2**
  Turbulence modification due to flame propagation
- **Task 3.3**
  DNS-based model discovery

**Objective 3**
Validation and exploration of parameter space for burner and AFS design

- **Task 4.1**
  Validation of LES models using hierarchical experiments
- **Task 4.2**
  Exploration of parameter space for flameholding and AFS systems
- **Task 4.3**
  Exploration of parameter space for flashback

Progress Bar:

# Publications

## Research publications from the program

- V. Sharma, Y. Tang and V. Raman. “Effects of Pitch Angle and Momentum Ratio on Flame Stabilization in Opposed Jets in Crossflow”. 18th International Conference on Numerical Combustion. May 8-11, 2022, San Diego, CA
- V. Sharma, Y. Tang and V. Raman. “A Computational Study on Effects of Injector Pitch Angle on Flame Stabilization in Opposed Jets in Crossflow”. 12th Mediterranean Combustion Symposium. January 23-26, 2023, Luxor, Egypt
- V. Sharma, Y. Tang and V. Raman. Stabilization of Hydrogen-enriched Jet Flames in a Crossflow [accepted to AIAA SCITECH 2024 Forum]

## Publications cited:


1. D1: Steinberg, A. M., Sadanandan, R., Dem, C., Kutne, P., and Meier, W., “Structure and stabilization of hydrogen jet flames in cross-flows,” Proceedings of the Combustion Institute, Vol. 34, No. 1, 2013, pp. 1499–1507. https://doi.org/10.1016/j.proci.2012.06.026,
2. D2: Fleck, J. L., Griebel, P., Steinberg, A. M., Arndt, C. M., Naumann, C., and Aigner, M., “Autoignition of hydrogen/nitrogen jets in vitiated air crossflows at different pressures,” Proceedings of the Combustion Institute, Vol. 34, No. 2, 2013, pp. 3185–3192. https://doi.org/10.1016/j.proci.2012.05.039
3. D3: Saini, P., Chterev, I., Pareja, J., Aigner, M., and Boxx, I., “Effect of Pressure on Hydrogen Enriched Natural Gas Jet Flames in Crossflow,” Flow, turbulence and combustion, Vol. 105, No. 3, 2020, pp. 787–806. https://doi.org/10.1007/s10494-020-00148-8
4. Barwey S, Raman V. A Neural Network-Inspired Matrix Formulation of Chemical Kinetics for Acceleration on GPUs. Energies. 2021; 14(9):2710. https://doi.org/10.3390/en14092710
5. AMReX: Software Framework for Block Structured AMR: https://doi.org/10.5281/zenodo.2555438

# Thank You

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# Cases Table

| Name | Fuel | Composition (v/v) | J | $U_j$ (m/s) | $Re_j$ | $U_{cf}$ (m/s) | $Re_{cf}$ | P (bar) | $T_j$ (K) | $T_{cf}$ (K) |
|---|---|---|---|---|---|---|---|---|---|---|
| D-1A | H2/N2 | 70/30 | 1.96 | 100 | 3000 | 55 | 44000 | 1 | 423 | 750 |
| D-1B | | 70/30 | 4.84 | 150 | 4500 | 55 | 44000 | 1 | 423 | 750 |
| D-1C | | 70/30 | 8.41 | 200 | 6000 | 55 | 44000 | 1 | 423 | 750 |
| D-2A | H2/N2 | 27/73 | 2.90 | 308 | 83000 | 300 | 450000 | 10 | 312 | 1185 |
| D-2C | | 27/73 | 1.10 | 125 | 35000 | 200 | 300000 | 10 | 312 | 1185 |
| D-3A | CH4/H2 | 60/40 | 102.10 | 19.9 | 17900 | 1.5 | 22000 | 10 | 298 | 465 |