Turbulent Flame Propagation Modeling in Premixed/Stratified Combustors

Application to Flame Flashback

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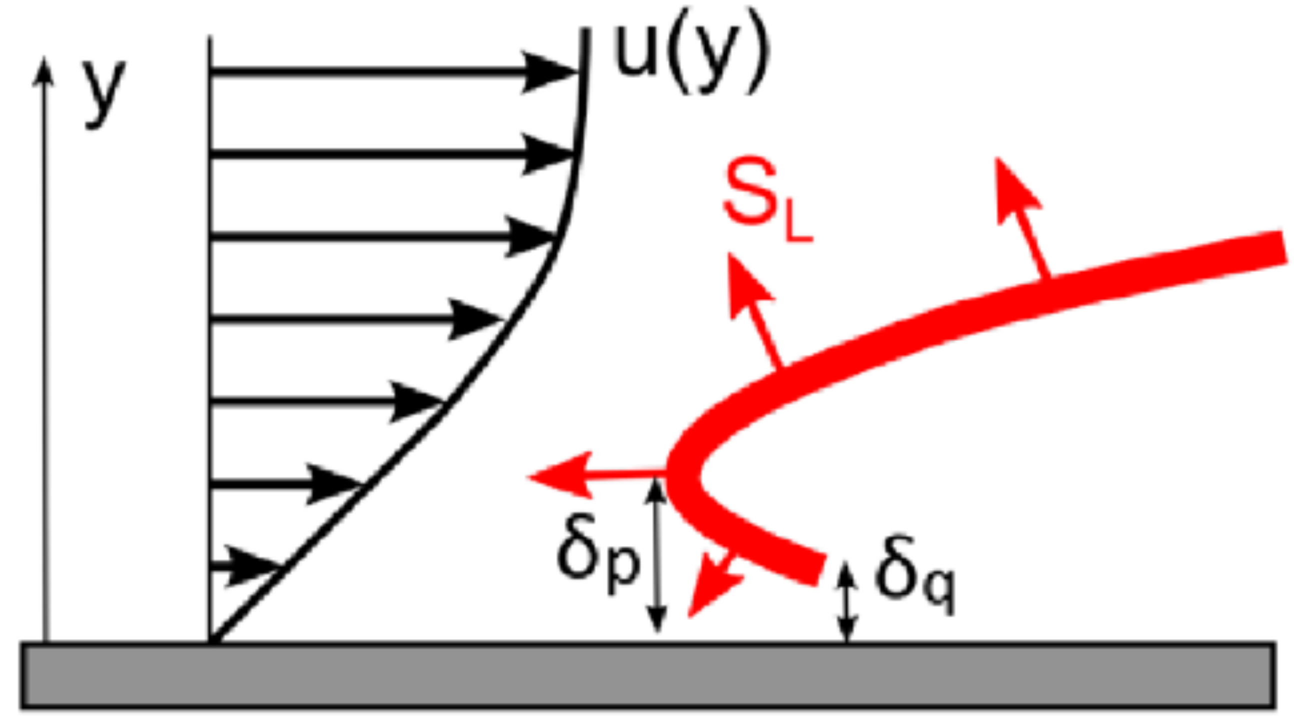
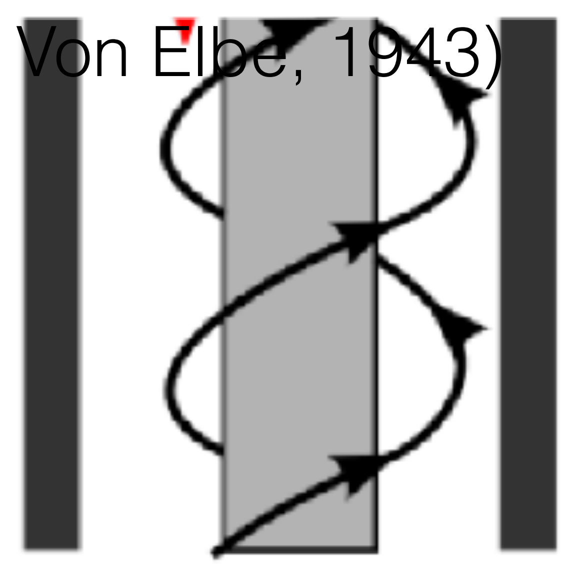
Background

- **Flashback in lean premixed combustor**
  - ➡ Nature of premixed flame, lead to severe damage
  - ➡ Transient and difficult to predict
    - Time scales of millisecond
  - ➡ Boundary layer flashback
    - Low momentum streaks
    - Reaction vs. near-wall quenching
- **Challenges in practical combustion device**
  - ➡ Complex geometry
  - ➡ Extension to stratified flame and even partially premixed



(Lewis and Von Elbe, 1943)



Project Objectives

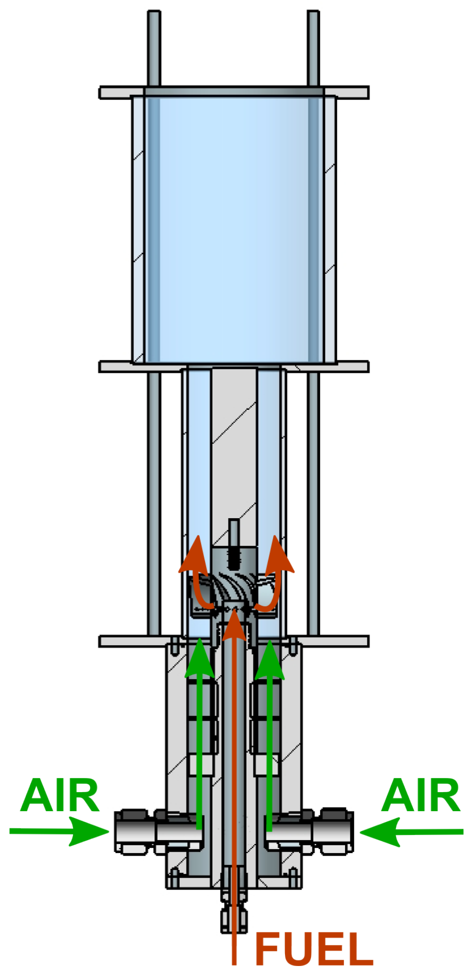
- **Goal: Understand flame structure and propagation in high pressure premixed/stratified mixtures**
  - ➡ Lean combustion in high strain conditions
  - ➡ Stratified combustion
  - ➡ Flame flashback in high hydrogen-content combustion
  - ➡ Staged combustion with hydrogen as fuel
- **Approach**
  - ➡ DNS/LES based modeling flames
  - ➡ Experiments of low and high pressure flames in stratified environments
    - Including flashback

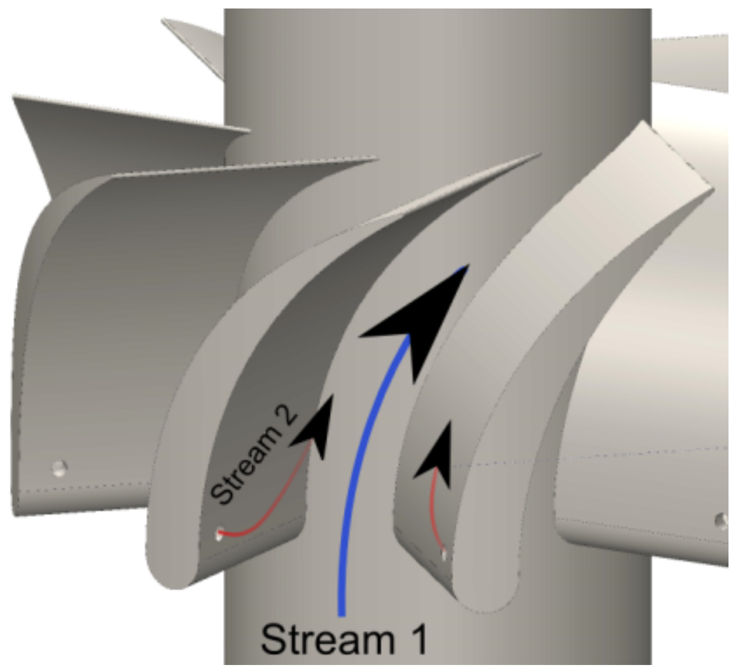
Outline

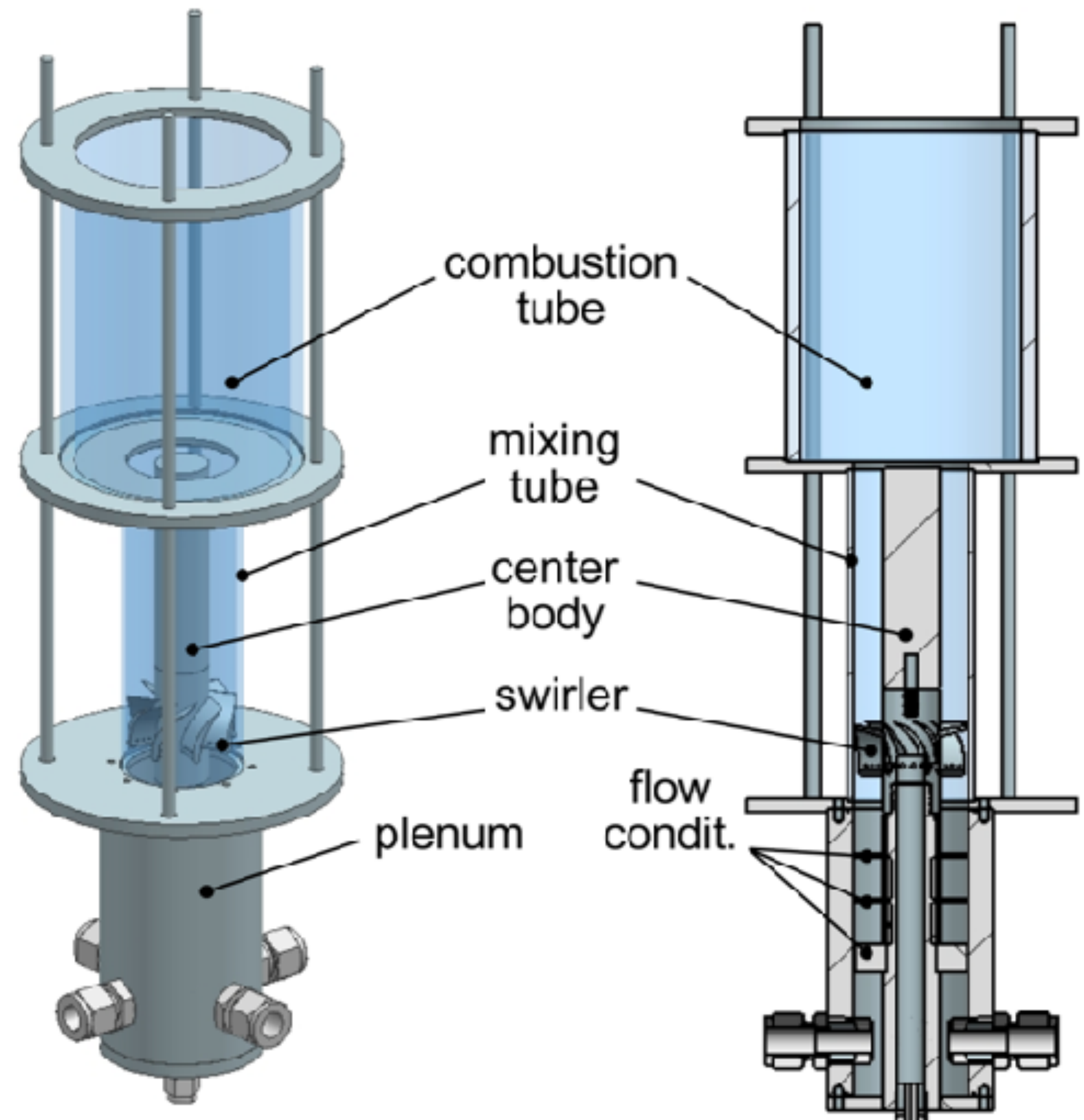
- **Experimental studies of flashback**
  - ➡ UT swirl burner
  - ➡ Low and high pressure test cases
  - ➡ Summary of findings
- **Computational modeling of premixed and stratified flames**
  - ➡ Solver development
  - ➡ Flamelet-based models
  - ➡ Validation test cases
  - ➡ Summary of findings

Stratified Flames and Flashback

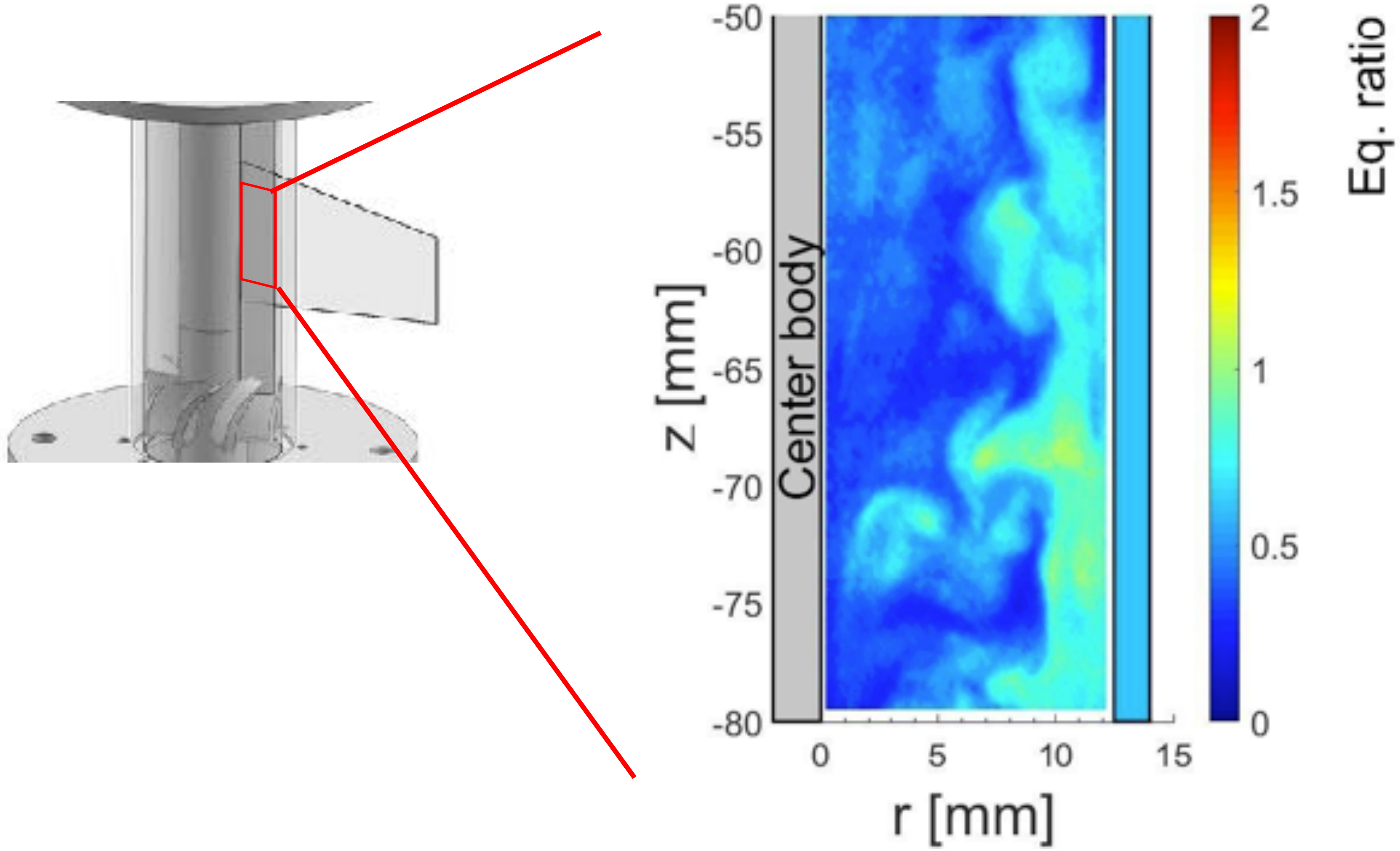
- Goal is to identify physical structure of flashback
- UT Swirl Burner with Nozzle-based Injection





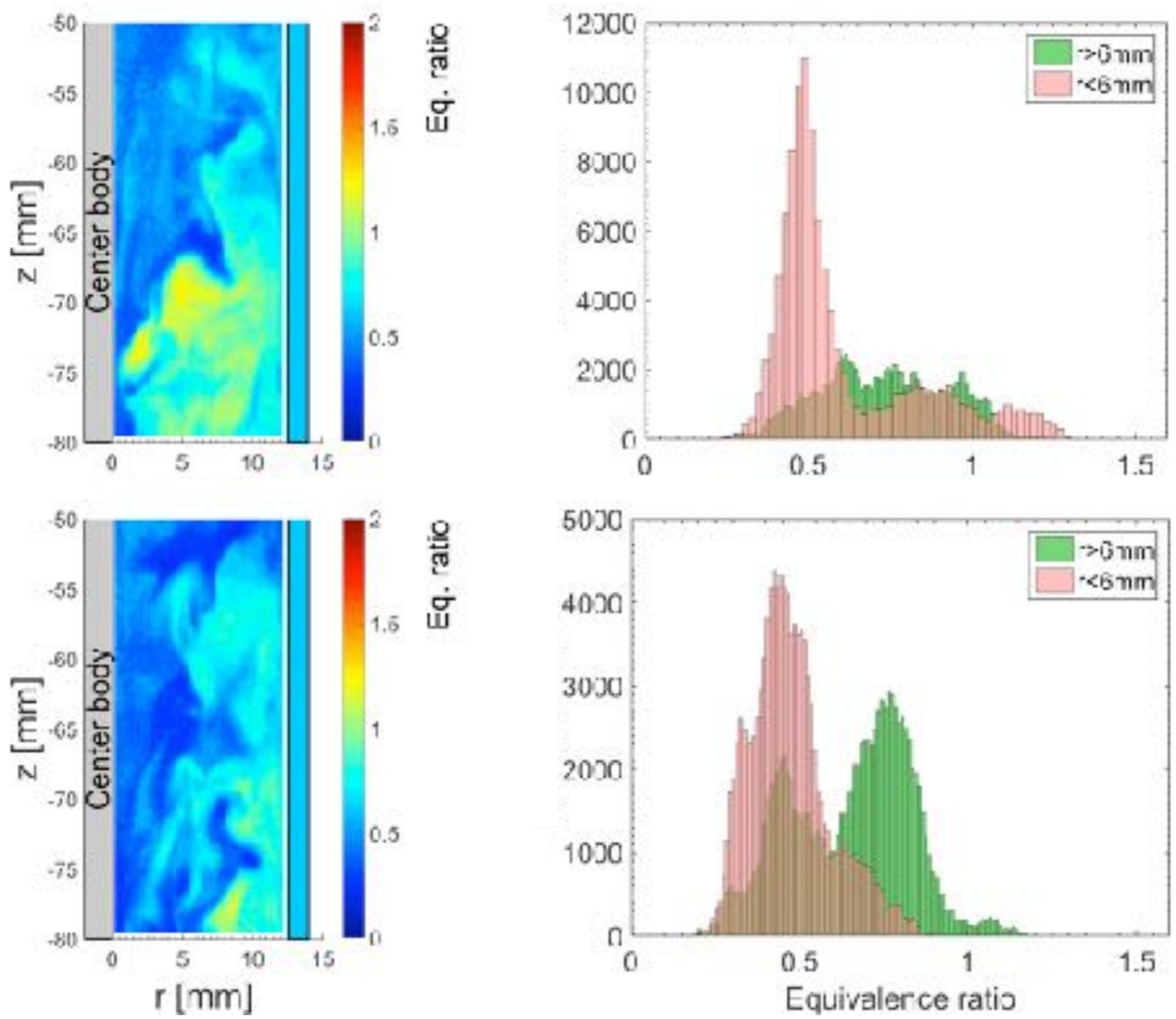


Demonstration of Stratification: Nonreacting Methane-air



- **Global equivalence ratio: 0.63**
- **Reh = 6100**
- **Average axial velocity: 2.5 m/s**
- **Non-reacting flow with acetone-seeded air through the fuel-nozzles**

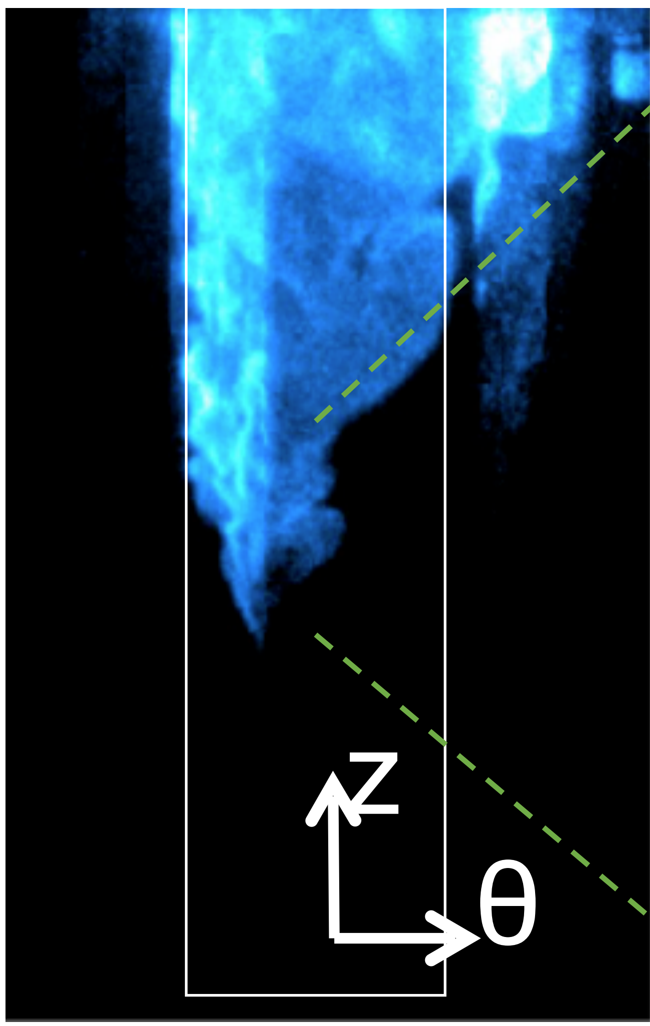
Equivalence ratio distribution snapshots



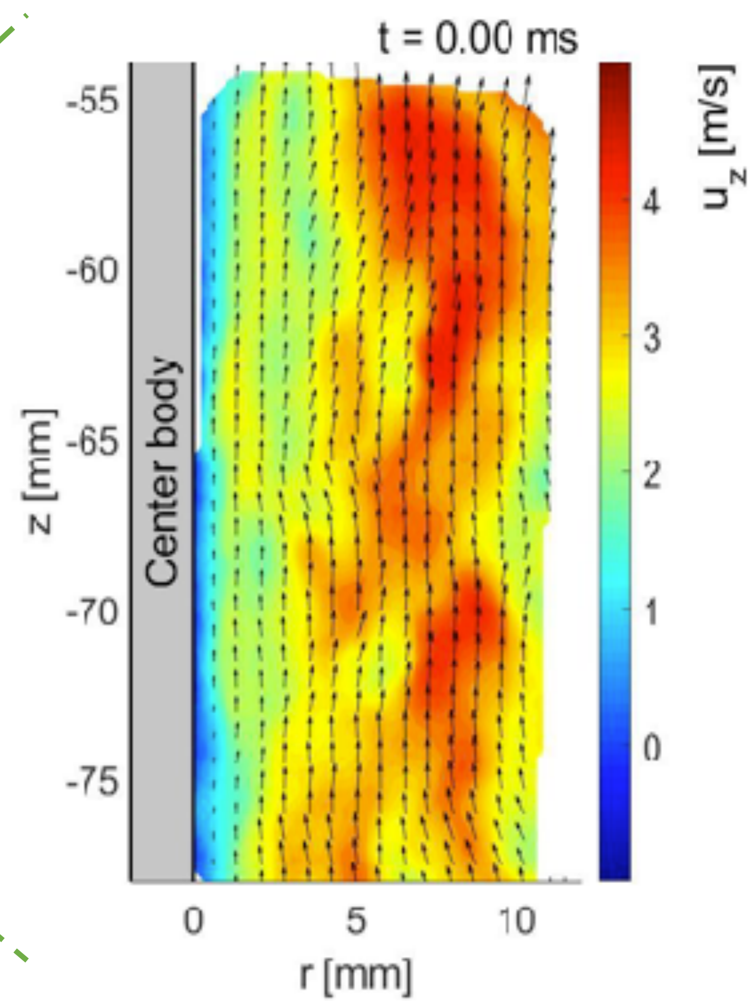
Histograms compare instantaneous equiv. ratio distribution in the inner half (r<6mm) to the outer half (r>6mm)

- **Flow was found to be stratified in an average sense**
- **Occasional presence of fuel-rich mixtures found close to the center-body**
- **Swirl and turbulence in the mixing tube may bring reactive pre-mixture close to the center-body boundary layer**

Propagation along the inner boundary layer



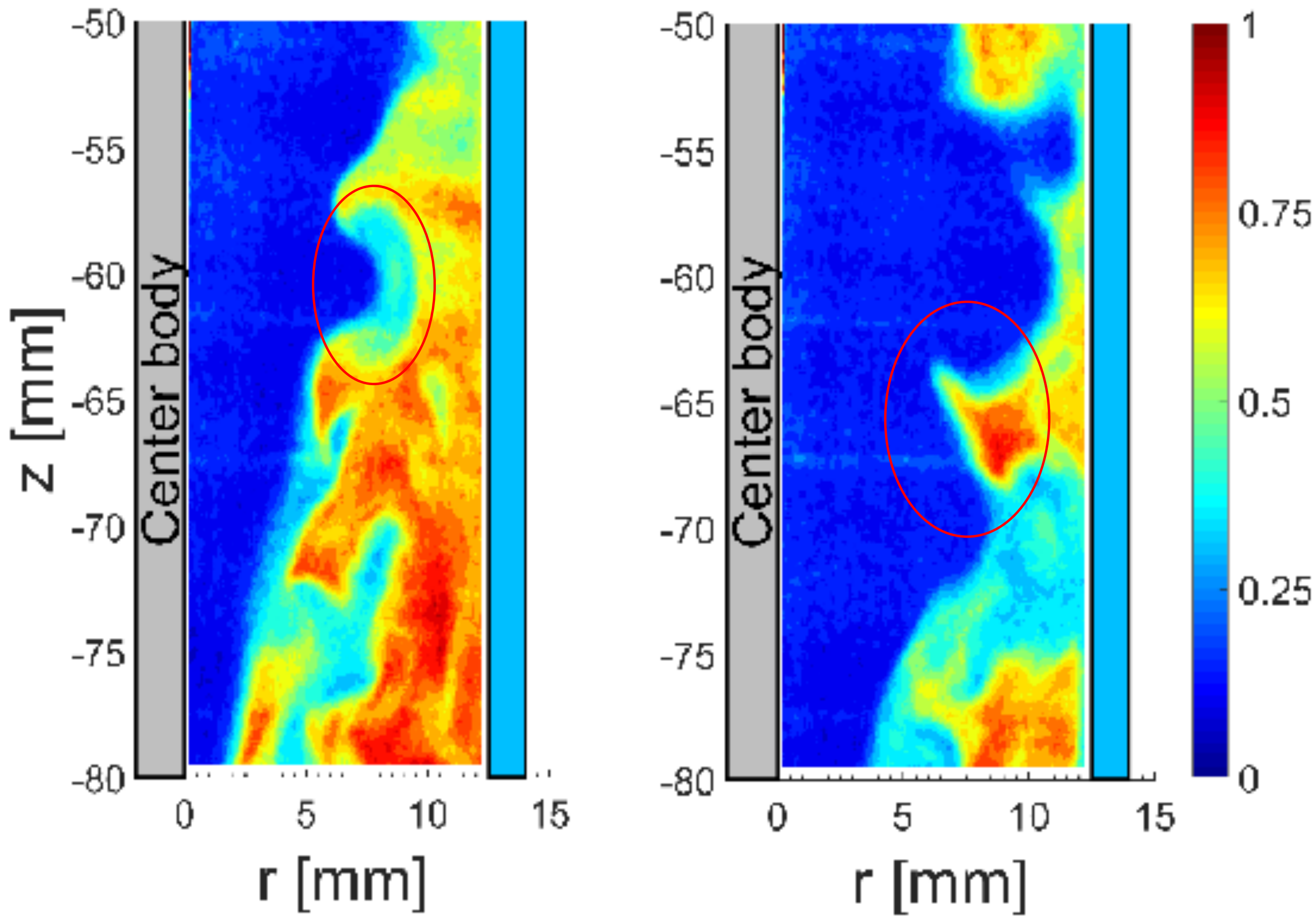
Luminosity image



Axial velocity map

- **Flame surface identified by evaporation of PIV seed particles (white region in the axial velocity map)**
- **Bright structures in the luminosity impose strong deflection of the approach flow**
- **Flame surface curvature is higher than the fully premixed flashback at same Re**

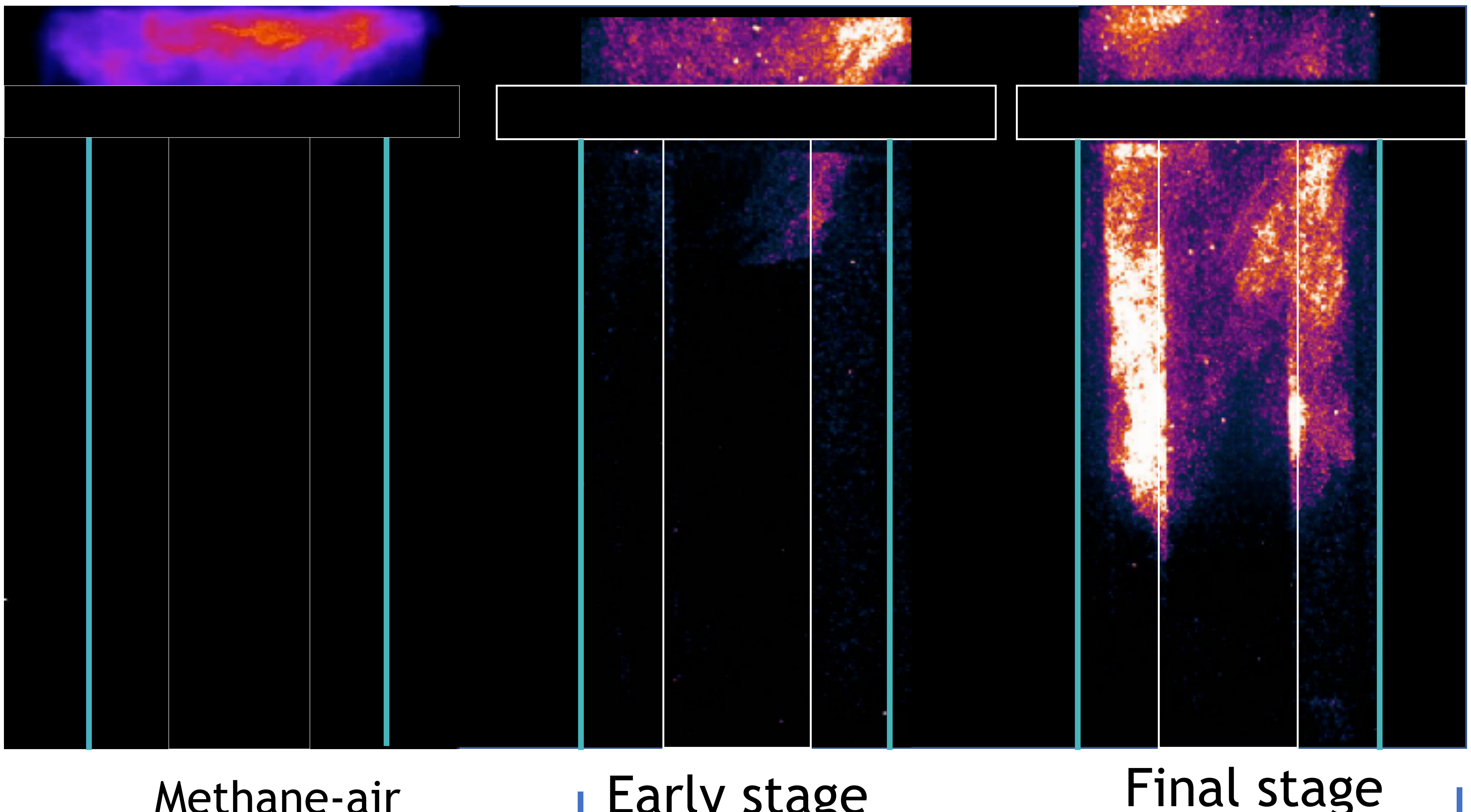
Acetone PLIF snapshots during Flashback



Normalized PLIF signal map during flashback

- **Instantaneous acetone PLIF signal maps were obtained for the reacting cases**
- **Flame curvature was found to be enhanced by the local distribution of the equivalence ratio**
- **Regions of positive and negative flame surface curvature are shown (in red circles)**

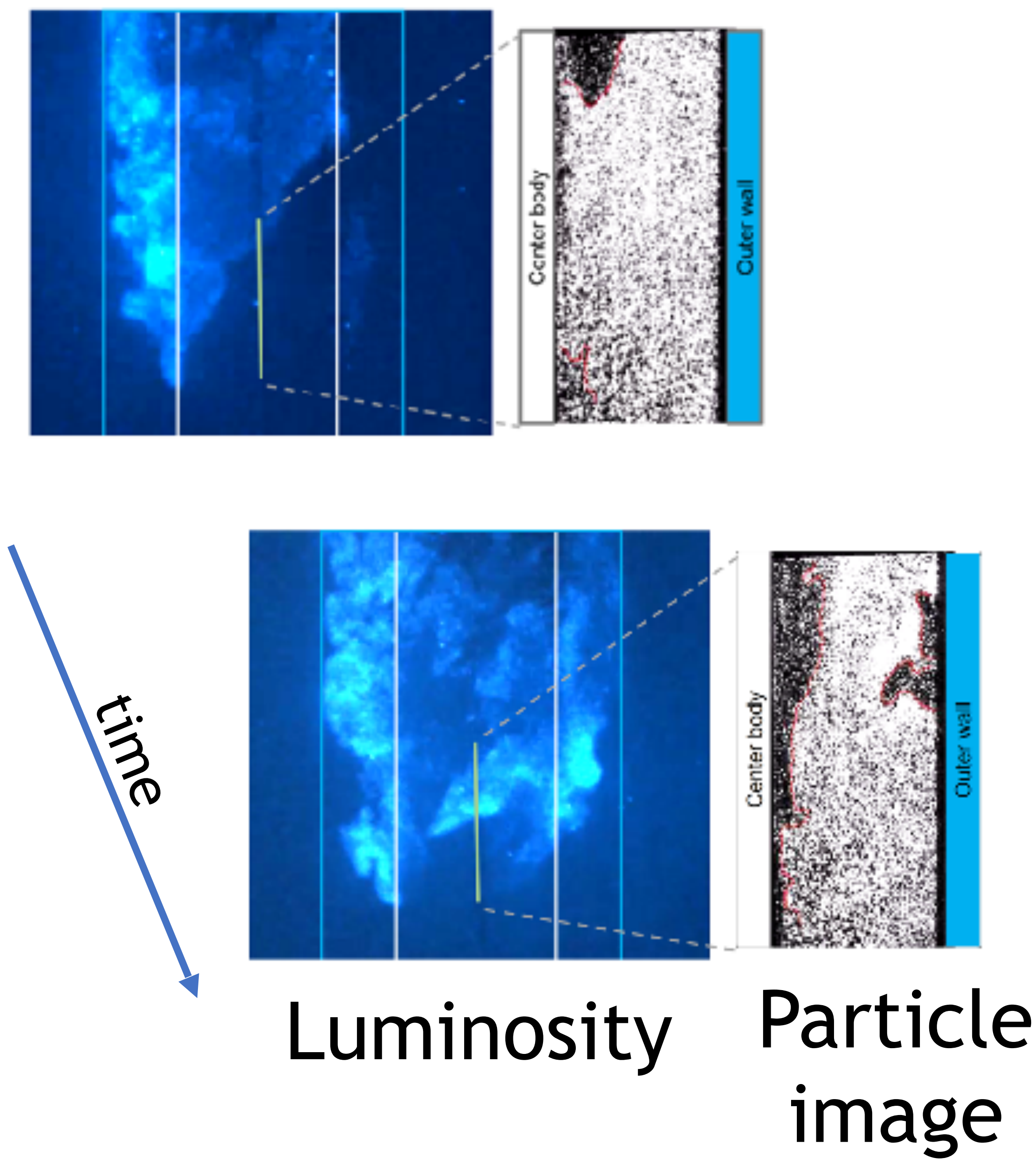
Effect of hydrogen-enrichment: Luminosity images



Flame propagates along inner wall for CH4 and H2 early stage

At later time H2 flame propagates on outer wall

Propagation along the outer wall



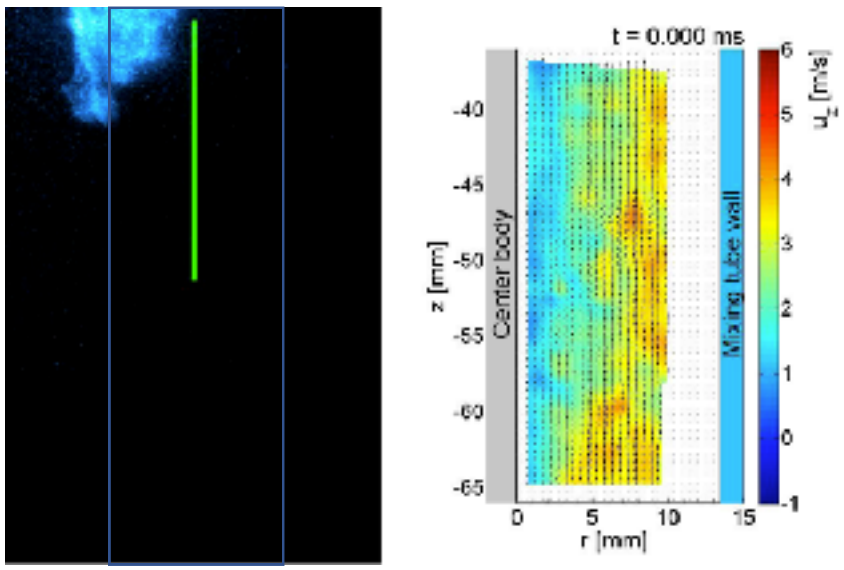
- **Flame starts propagating along the center-body boundary layer,**

  ➡Switches to the outer wall after a few milliseconds

- **Simultaneous Mie scattering images show the thin acute-tipped flame-strand propagating along the outer wall**

- **The outer wall propagation continues until the flame stabilizes itself on the fuel ports**

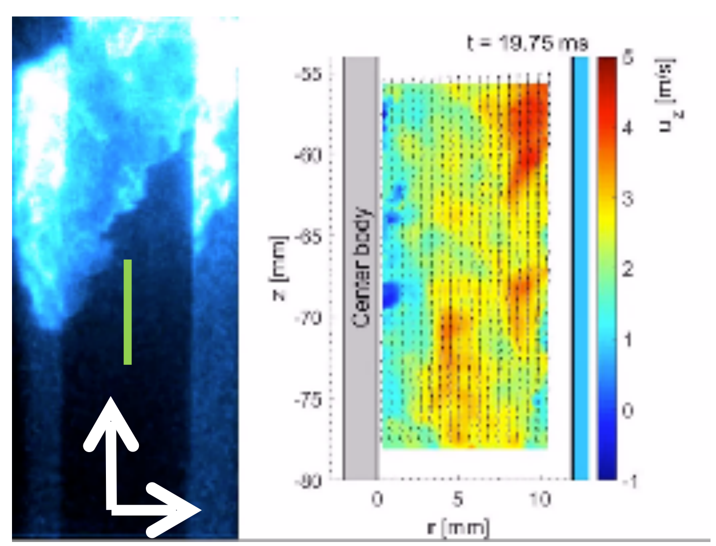
Elevated pressure flashback: Premixed vs Stratified



Premixed

Flow parameters

- Fuel: Methane
- Average axial velocity: 2.5 m/s
- Pressure: 3 atm



Stratified

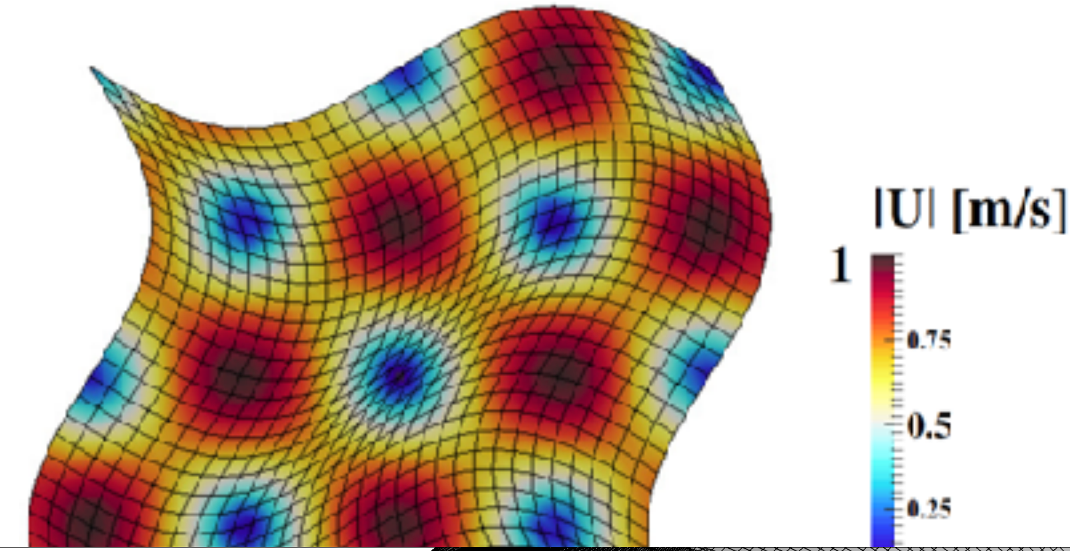
- **Premixed flashback at elevated pressures exhibit very small radial spread,**
- **Stratified flame flashback stops at an intermediate location in the mixing tube**
- **The flame brush is more wrinkled and exhibits large radial spread reaching up to the outer wall**

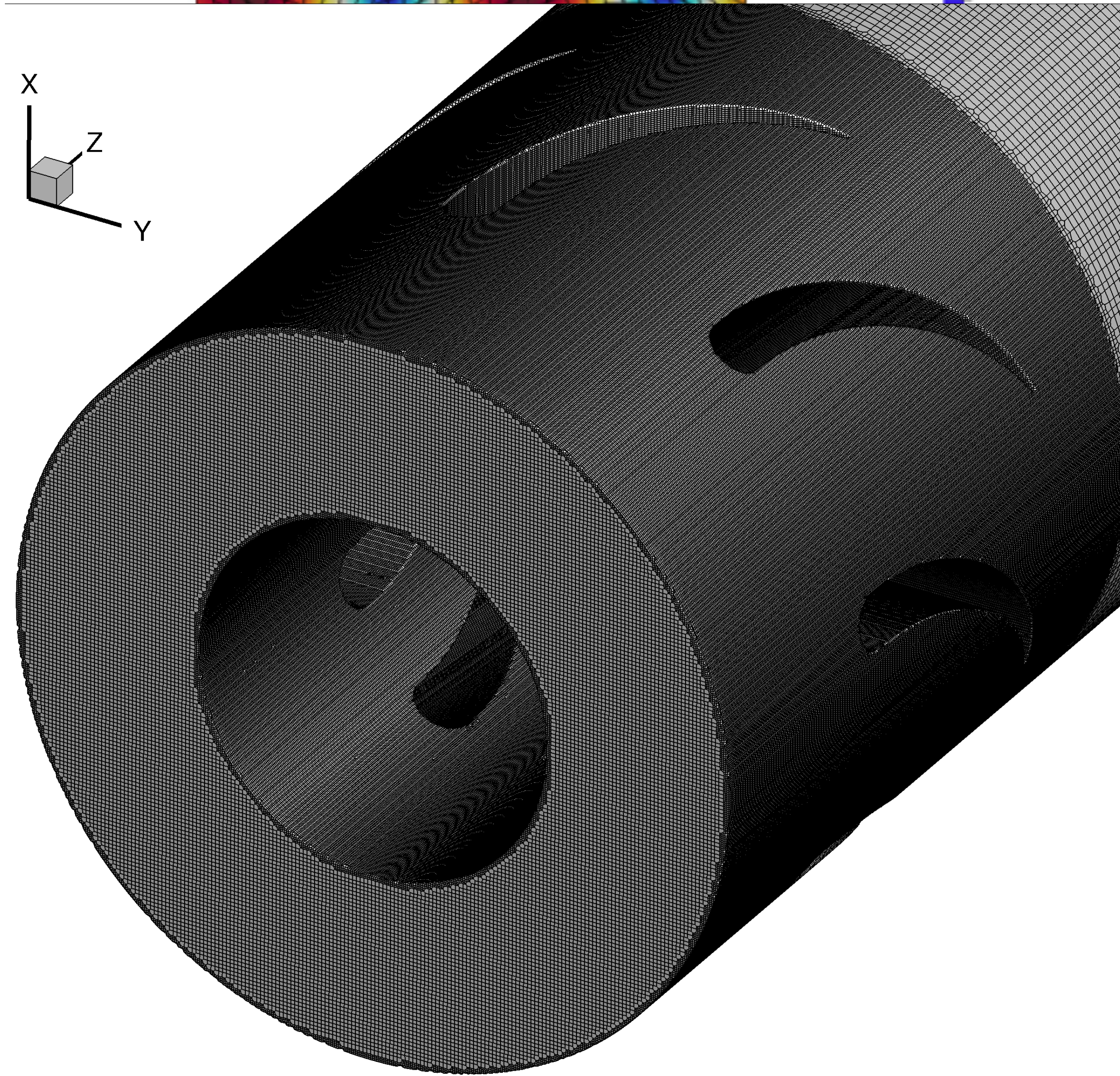
Summary of Findings

- **A methodology for initiating flashback was developed**
  - ➡ Advanced laser diagnostics used
- **Stratification leads to arresting of flame flashback**
  - ➡ As expected
  - ➡ But, hydrogen seems to get around this solution
- **At elevated pressures, flashback behavior is similar**
- **Radial spread of flame brush larger for stratified flame**
  - ➡ Flame propagation through regions with equivalence ratios outside flammability limit

Numerical Setup

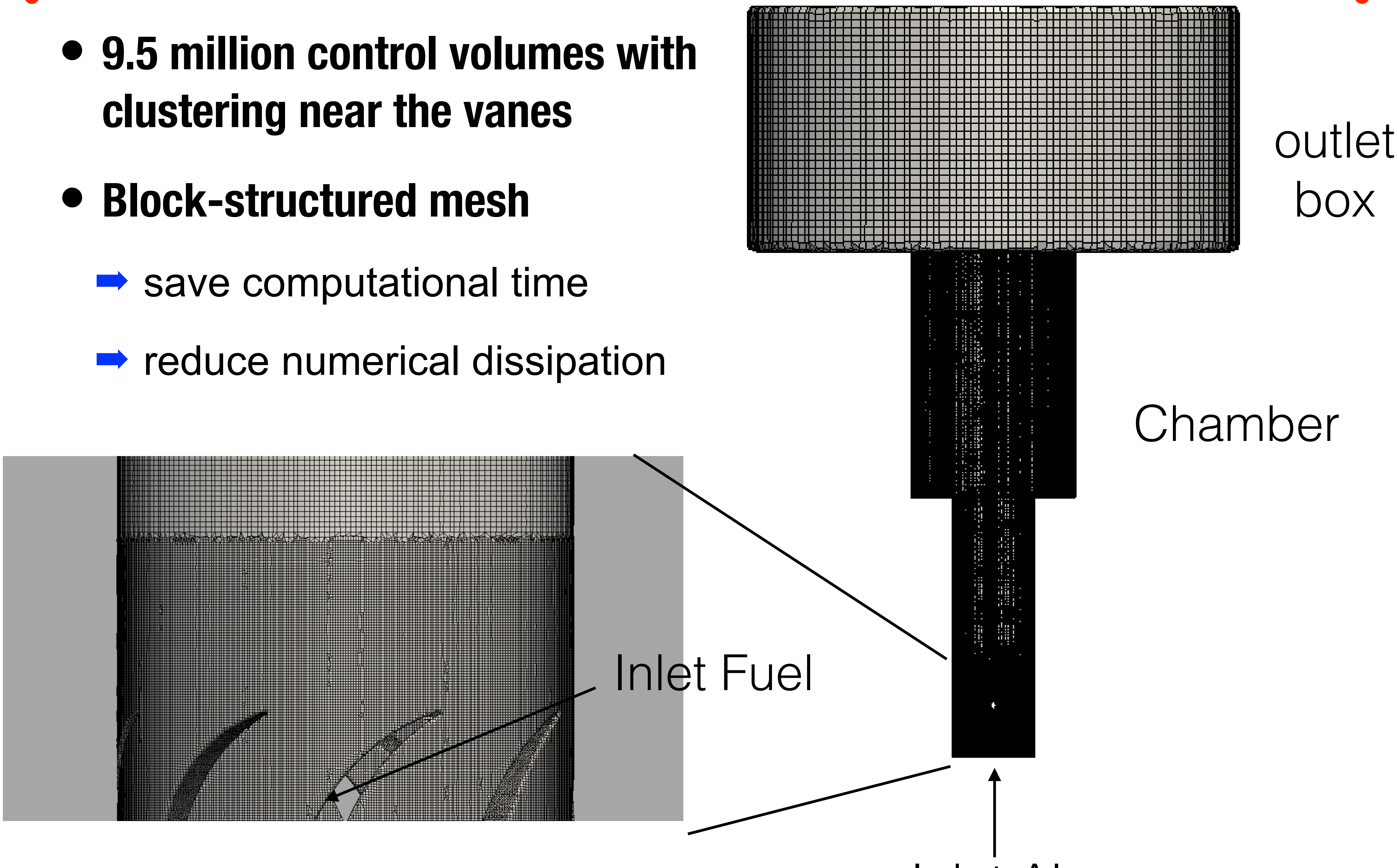
- **Variable density low Mach solver - umFlameletFoam**
  - ➡ OpenFOAM based
  - ➡ Low Mach solver
  - ➡ Minimize dissipation
- **10M hexahedral-dominant mesh**
  - ➡ Local refinement at swirler
- **Run for 10,000 core hours on 1008 processors**





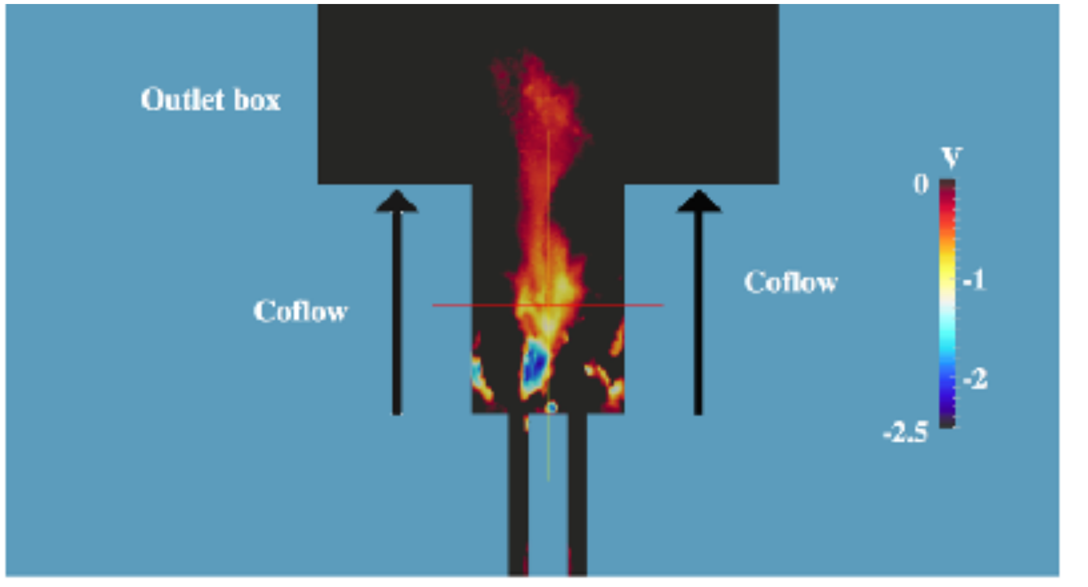
Numerical details

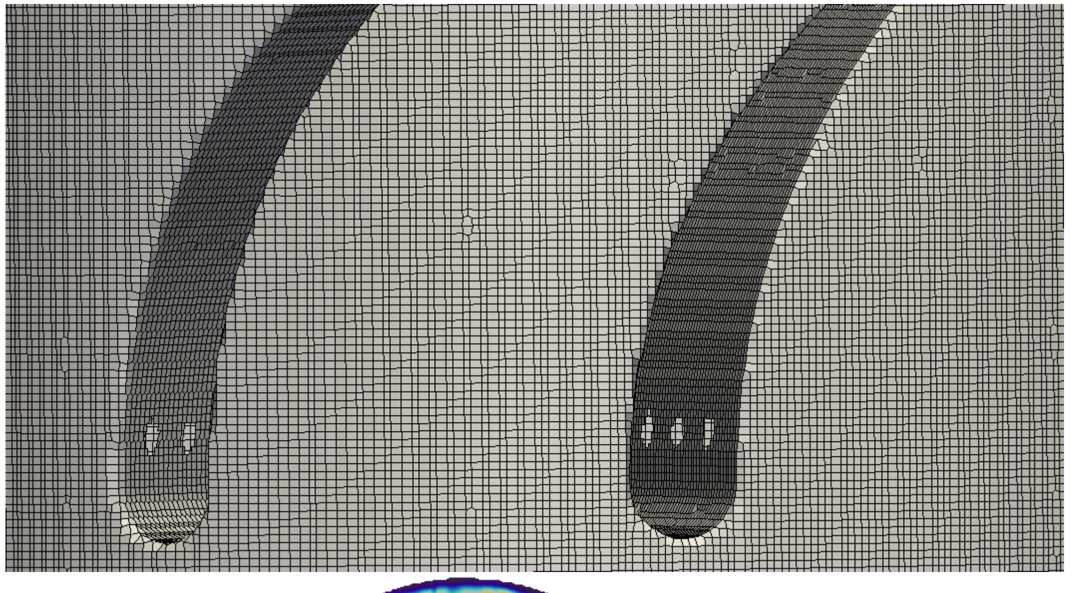
- **9.5 million control volumes with clustering near the vanes**
- **Block-structured mesh**
  - ➡ save computational time
  - ➡ reduce numerical dissipation

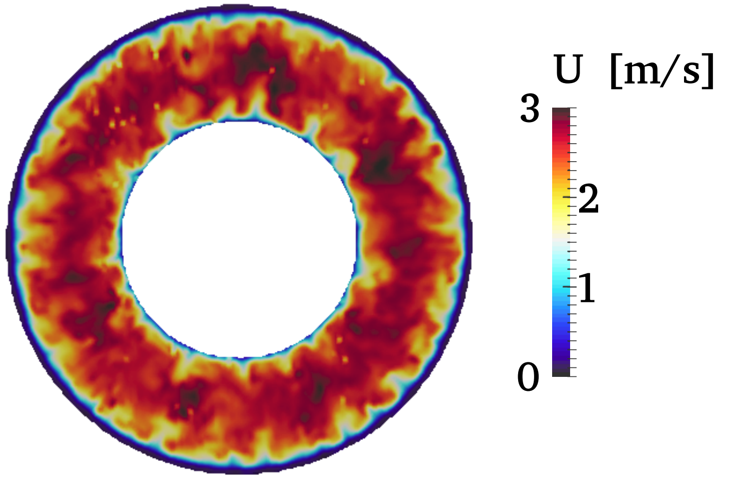


Boundary conditions

- **Role of outlet box**
  - ➡ Drive vortices outside the chamber
  - ➡ Dissipate the vortices
- **Fuel Inlet**
  - ➡ Dirichlet BC, fixed in time
  - ➡ Mass flow rate matches experiments
- **Turbulent velocity inlet**
  - ➡ From auxiliary annulus simulation



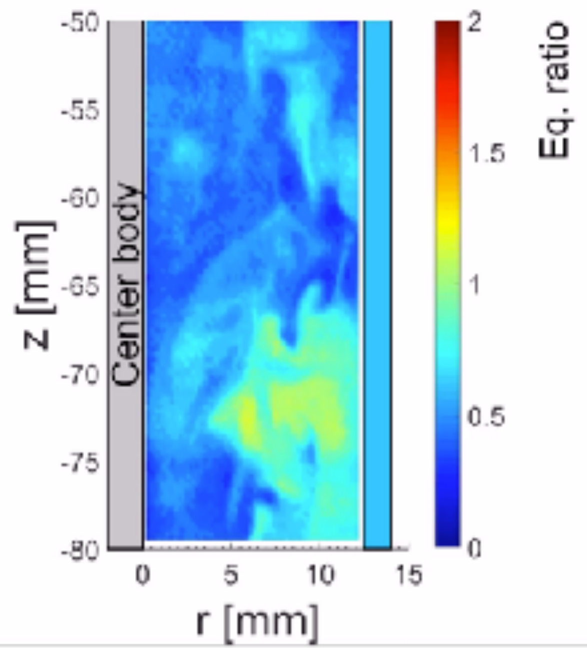




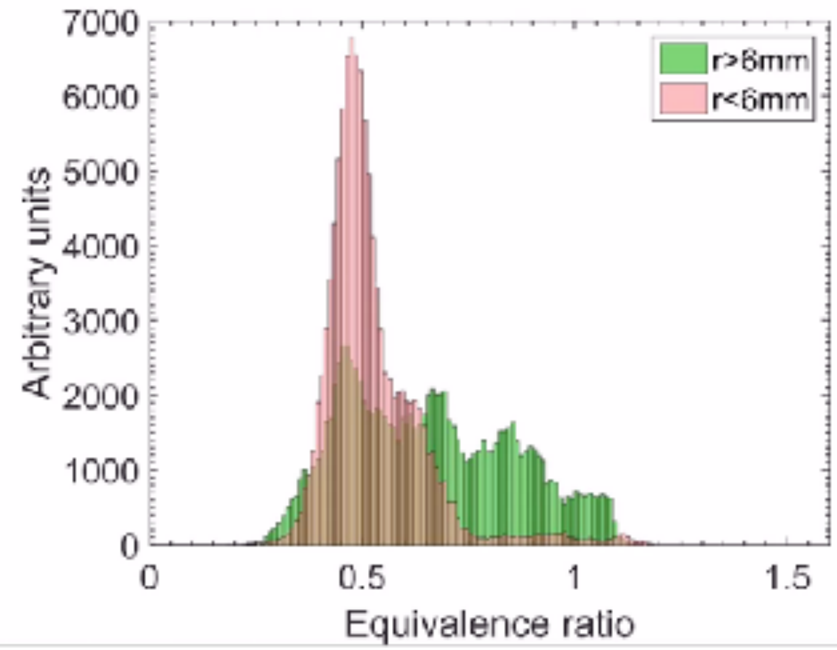
Fuel Distribution

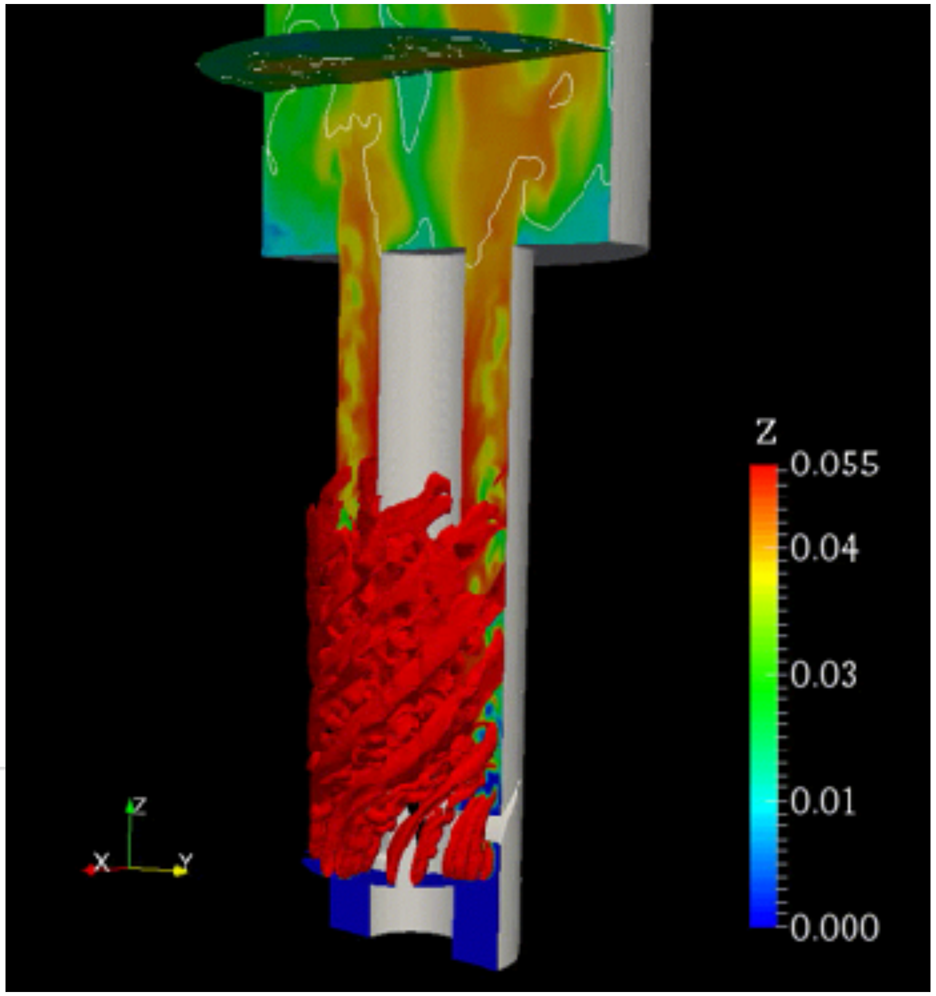
- **Nozzle injection causes non-uniform fuel distribution in the radial direction**

ACETONE PLIF



HISTOGRAM OF FUEL CONCENTRATION



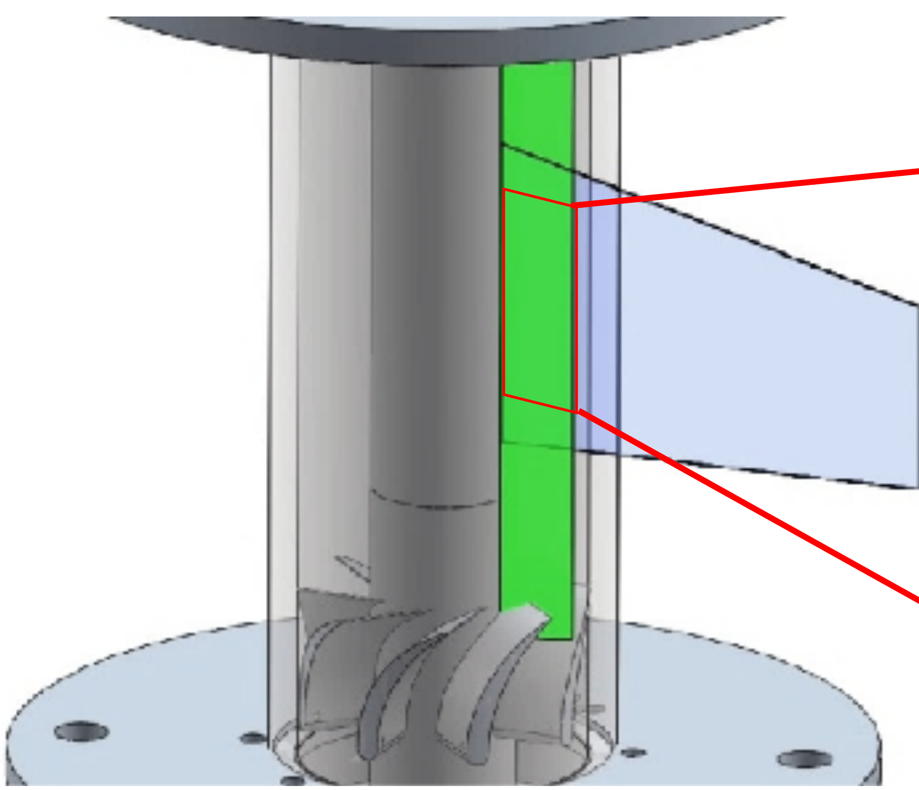


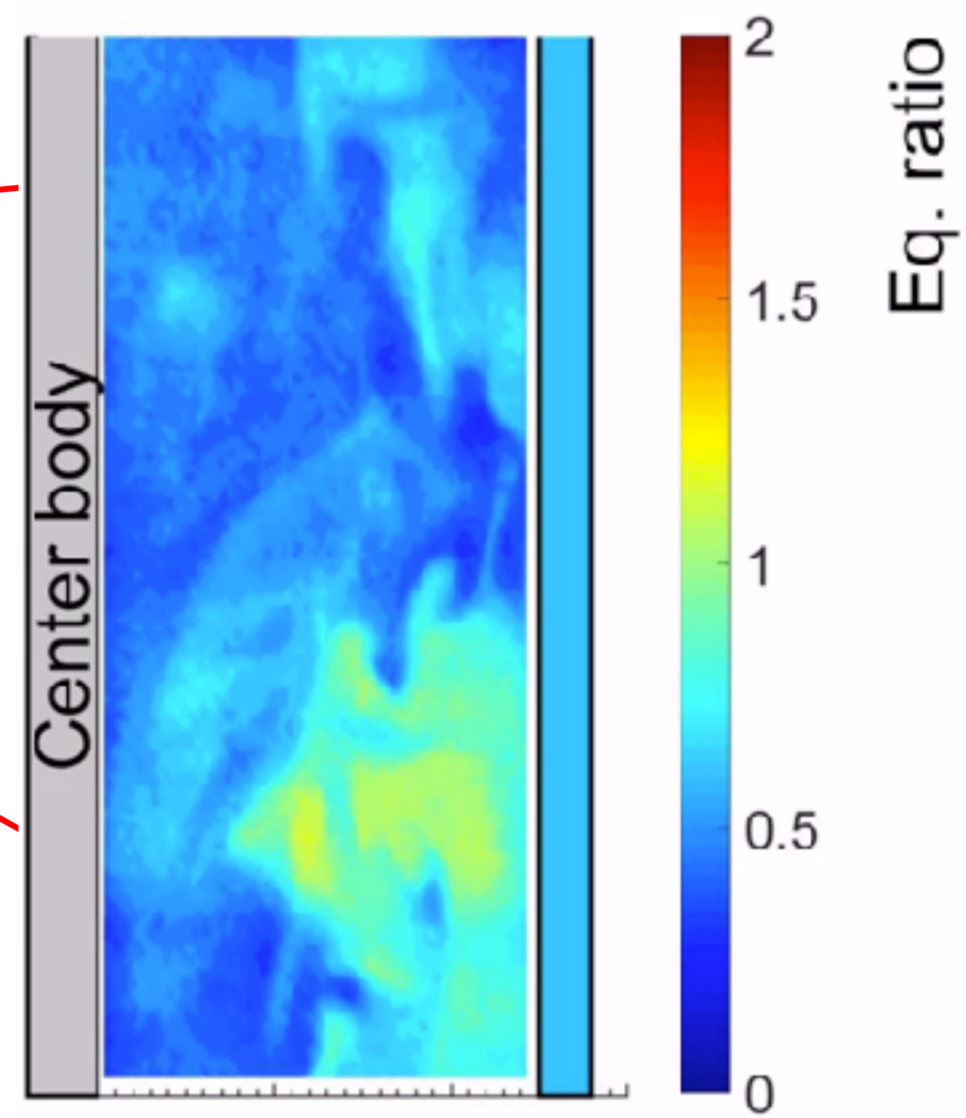
- **Richer mixtures closer to outer wall**

Non-reacting Case Study

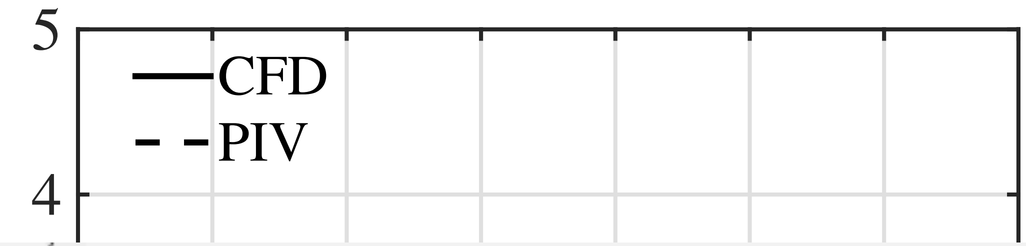
- **Fuel stream replaced by acetone seeded air**
- **PLIF measurement of equivalence ratio**

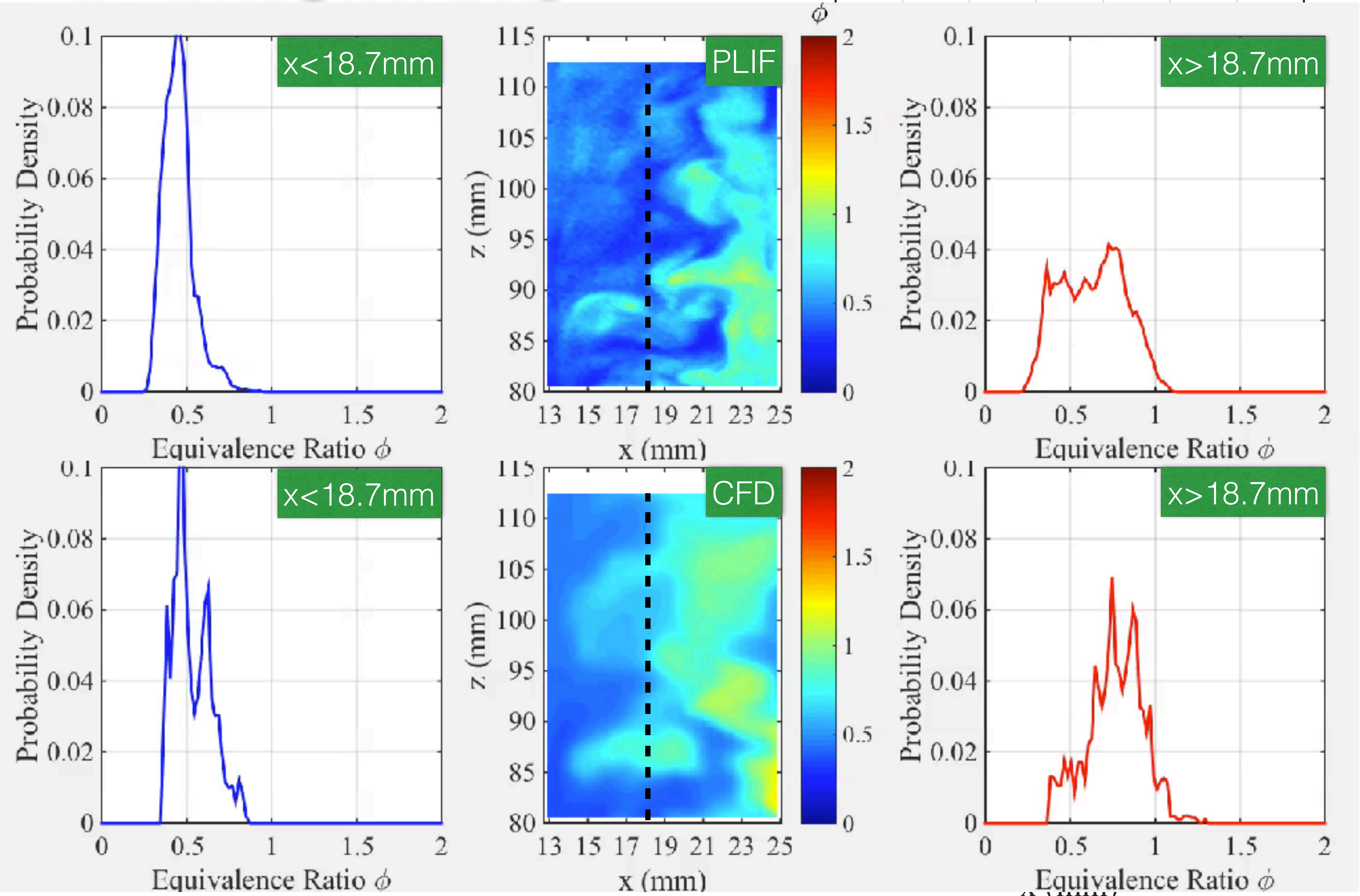
Operating Condition
Temperature : 300K
Pressure : 1atm
Global equivalence ratio: 0.5
Bulk velocity : 2.5m/s





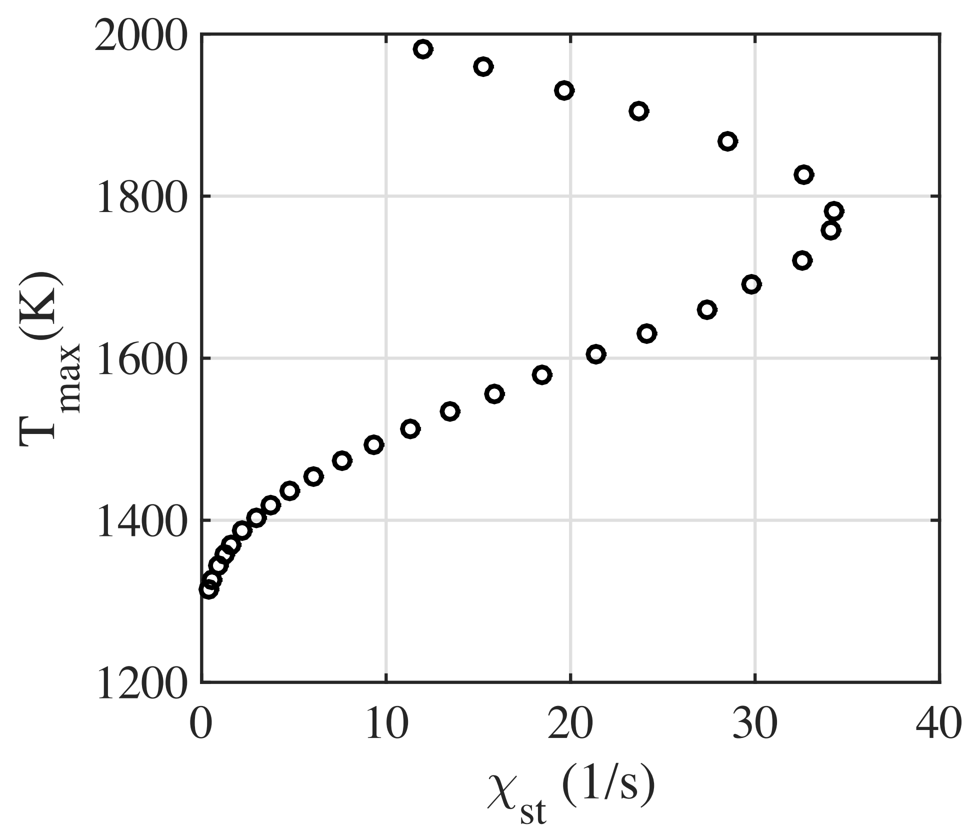
Non-reacting Case Study

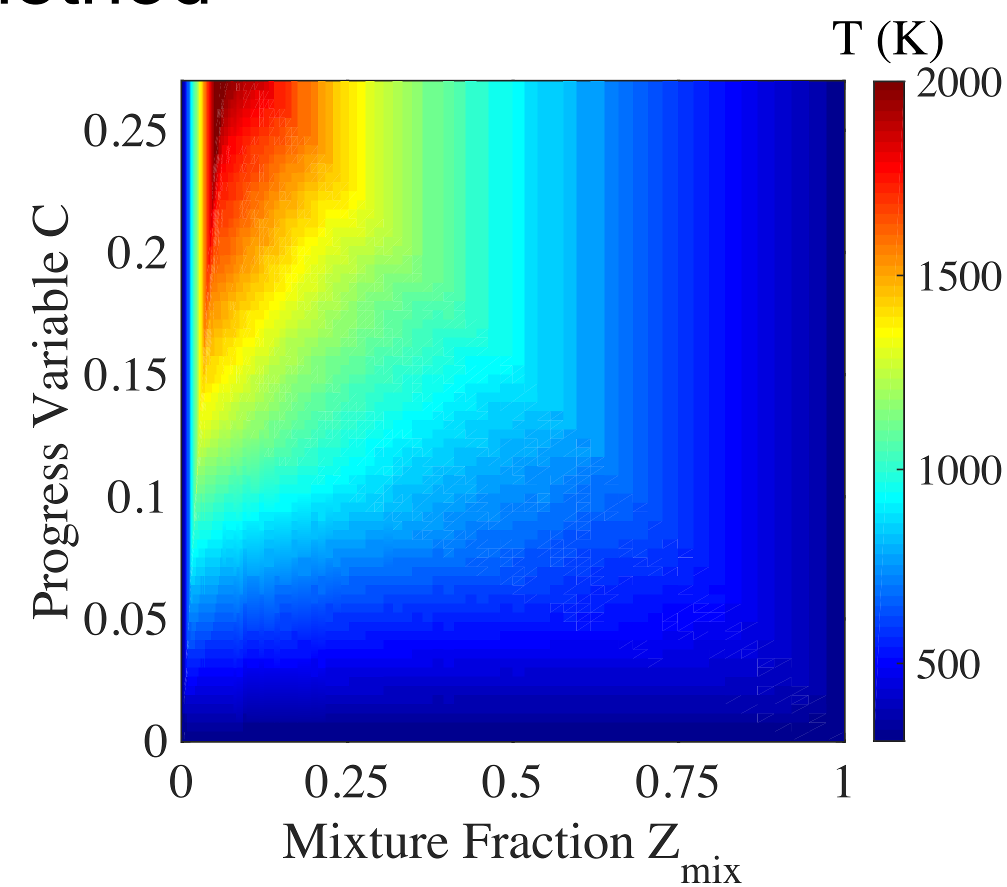




Modeling Approach

- **Based on large eddy simulation(LES)/flamelet approach**
- **Stratified mixtures**
  - ➡ Mixture fraction and progress variable required
  - ➡ Flamelet progress variable (FPV) method





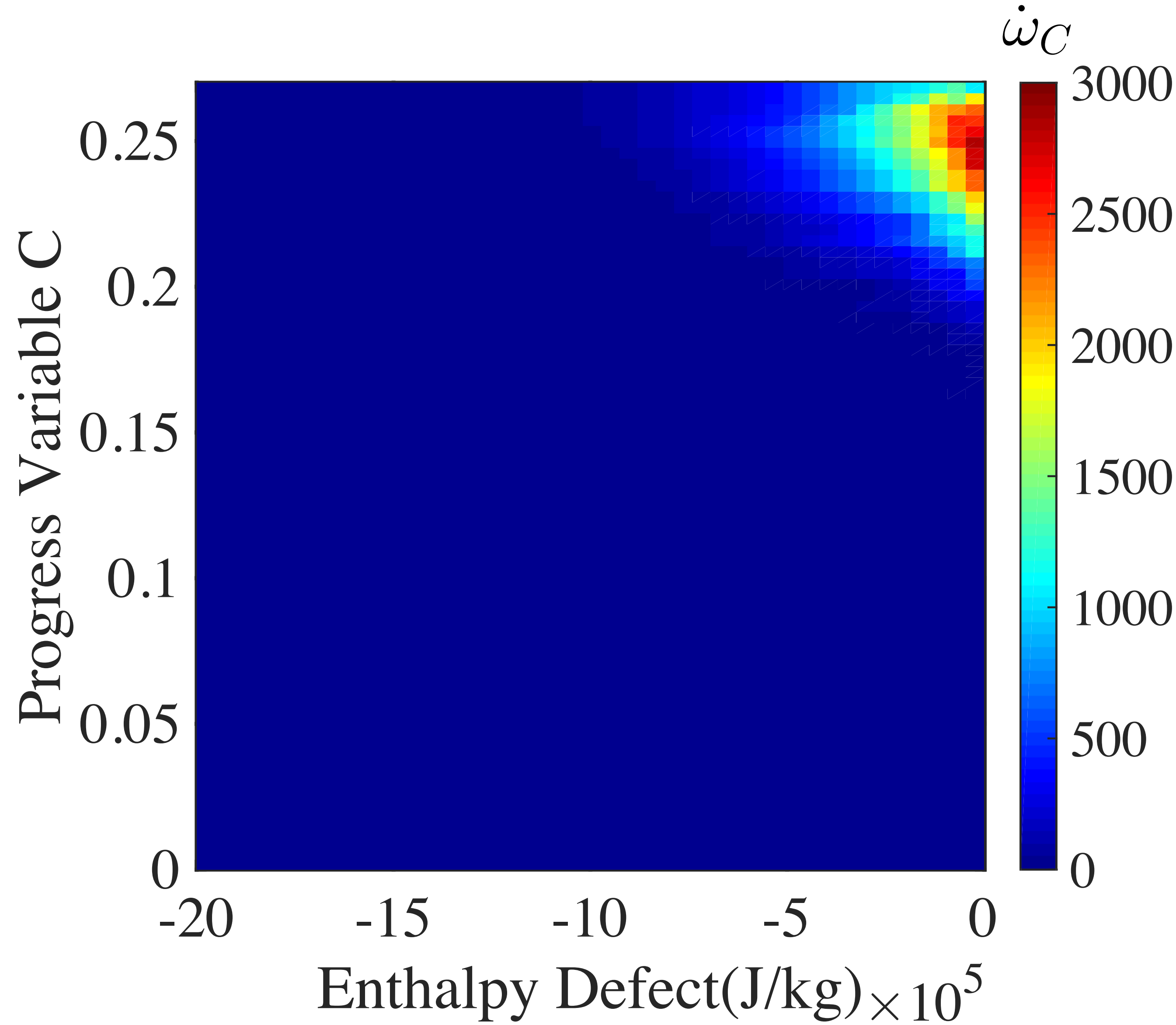
- **Heat loss**
  - ➡ Additional coordinate for enthalpy defect

Heat Loss Modeling

- **Introducing heat loss into flamelet**
  - ➡ Modify flamelet equations to account for heat loss

$$\frac{\rho C_p \chi}{2}\frac{\partial^2 T}{\partial Z^2} = \dot{\omega}_h - \lambda \frac{T(Z) - T_w}{\delta}$$

  - ➡ Fourier heat loss term, varied based on δ



- **Transport equation of enthalpy defect**

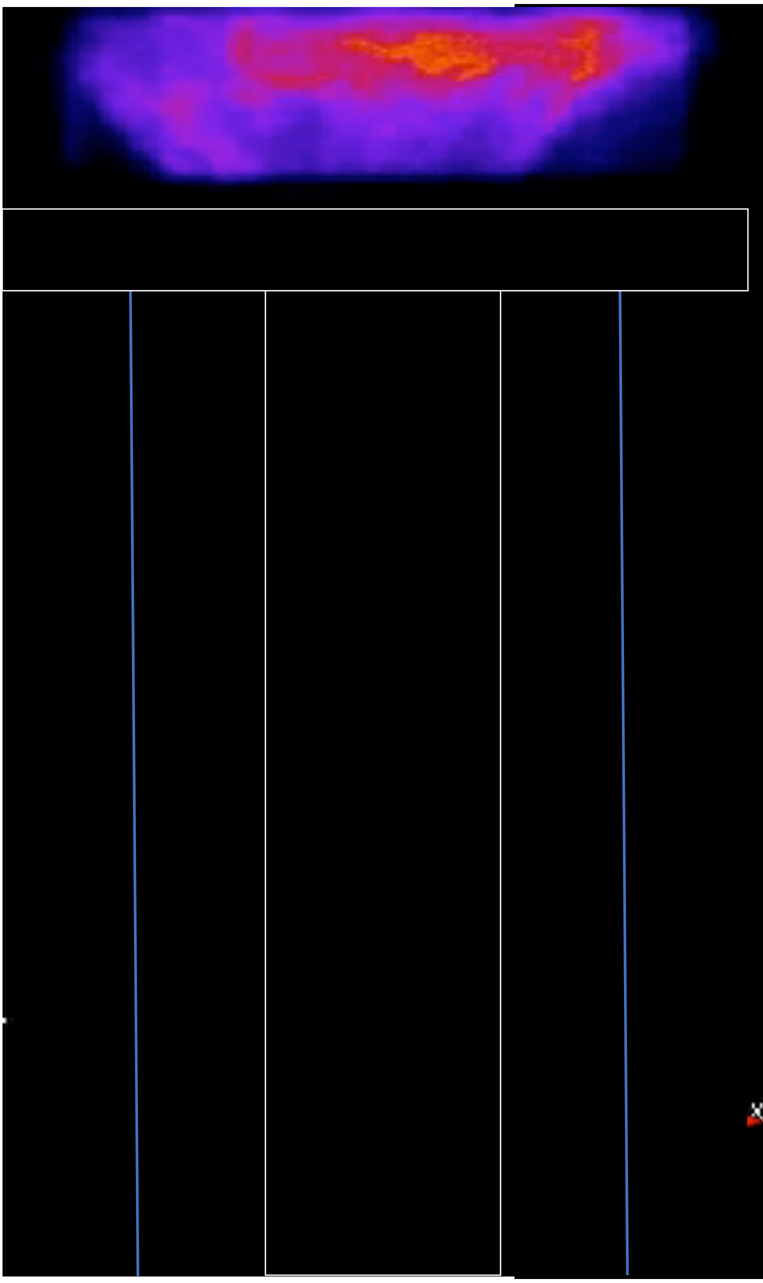
$$H = h_{tot} - h_{tot,Ad}$$

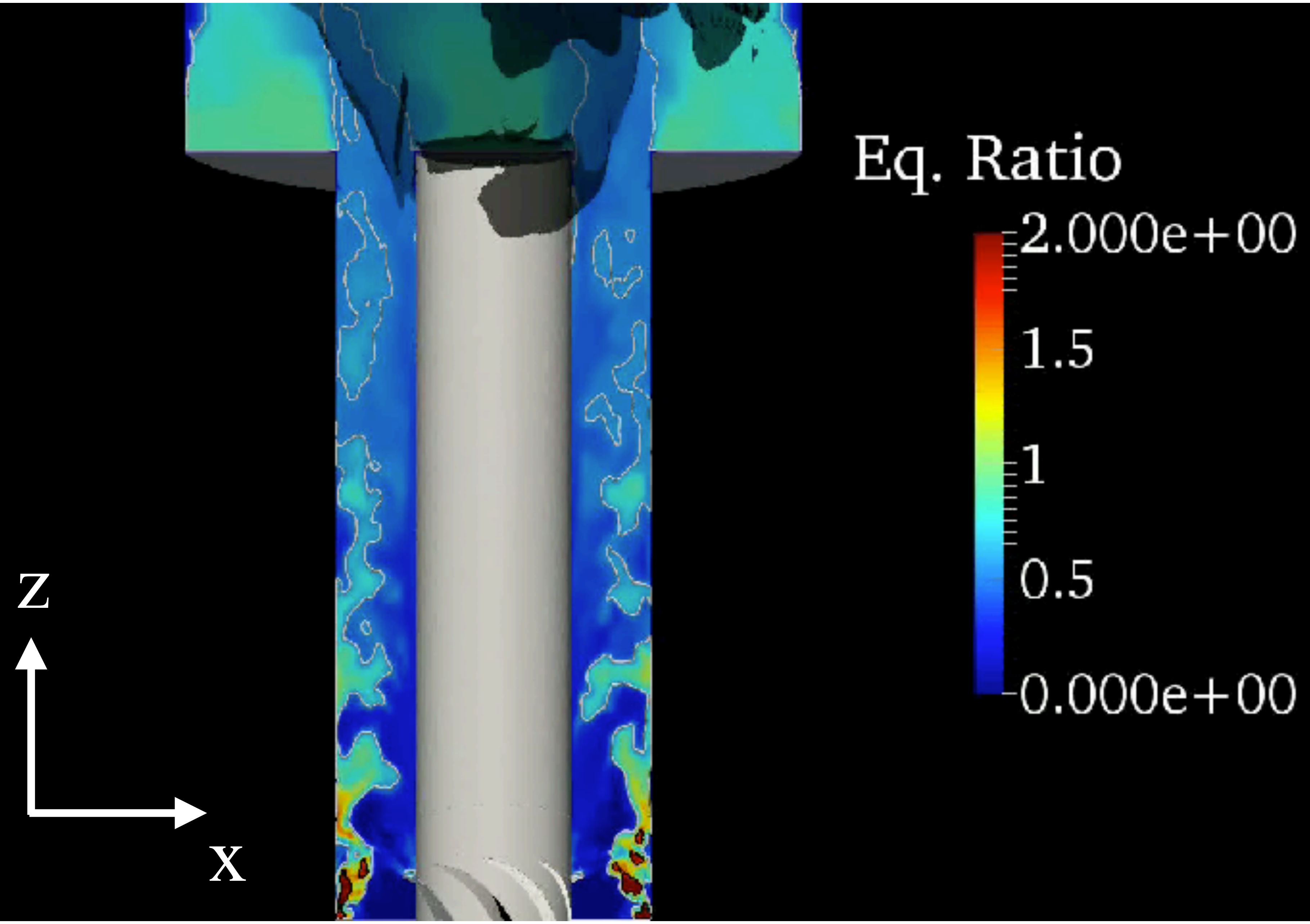
$$\frac{\partial \bar{\rho}\tilde{H}}{\partial t} + \nabla \cdot \left(\bar{\rho}\tilde{v}\tilde{H}\right) = \nabla \cdot \left(\frac{\mu_T}{Pr}\nabla \tilde{H}\right) + \nabla \cdot (\lambda \nabla T) - \nabla \cdot (\lambda_{Ad} \nabla T_{Ad})$$

Adiabatic Reacting Case Study

Chemiluminiescence

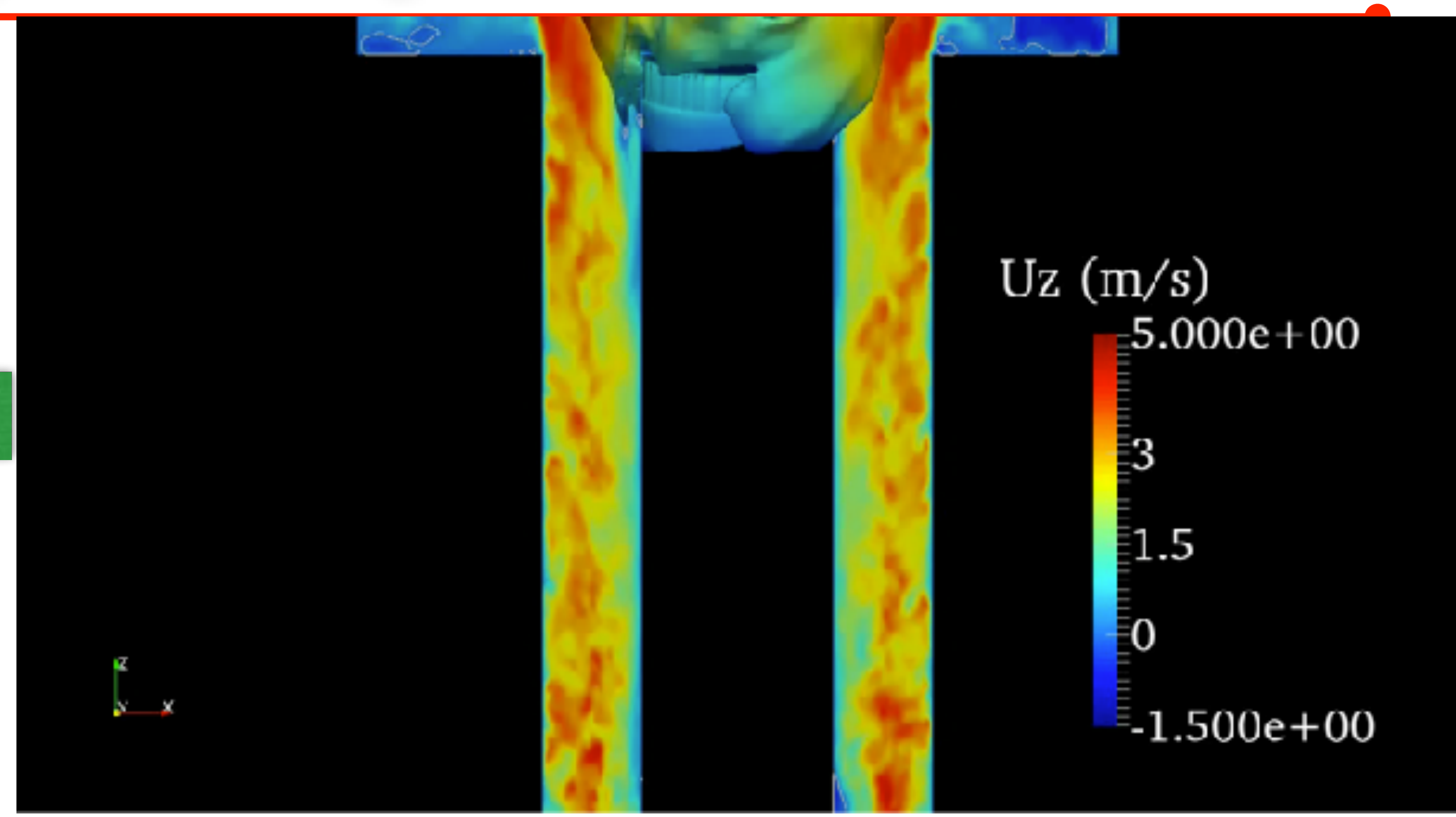
CFD



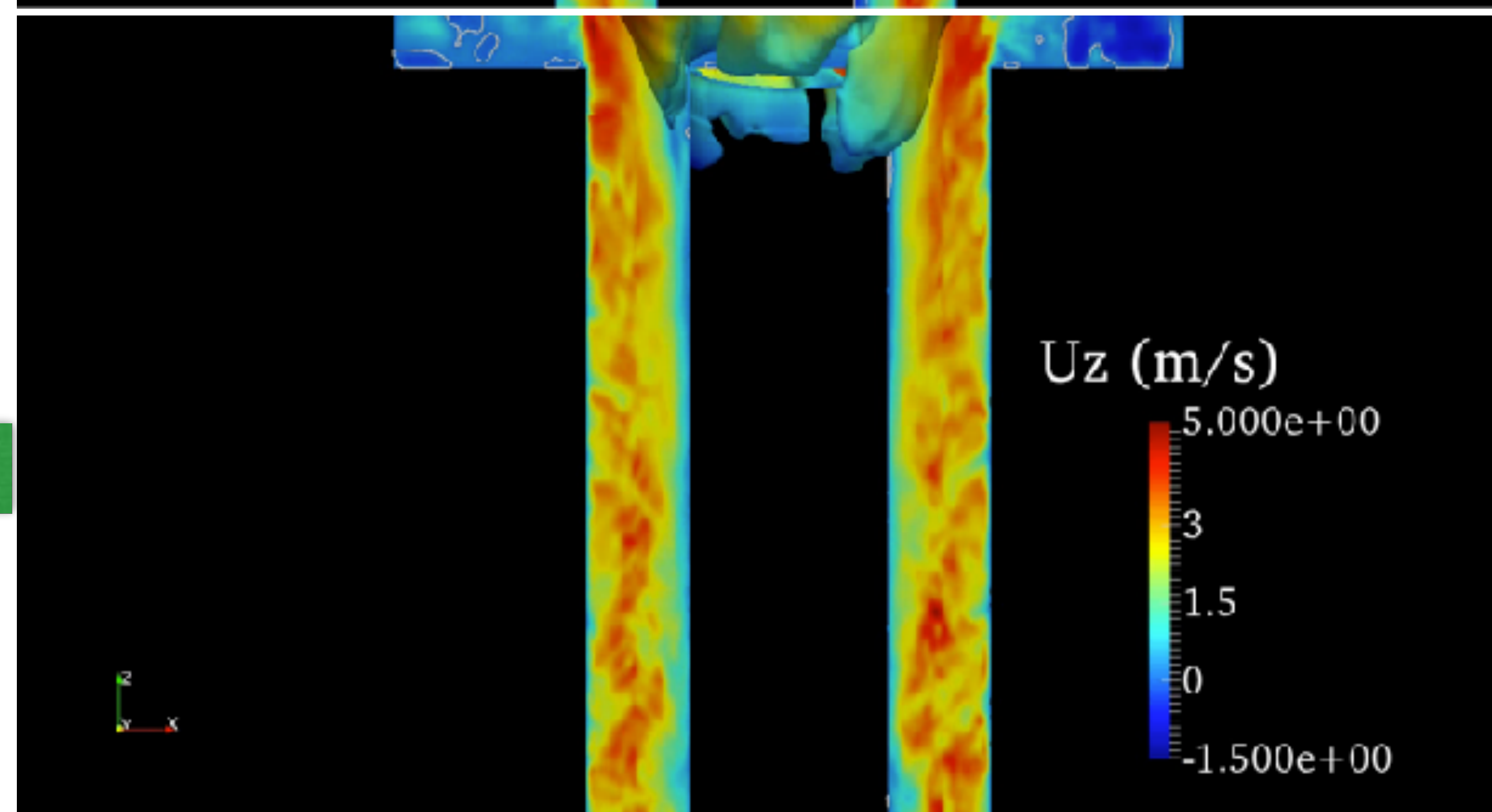


Non-adiabatic Reacting Case Study

Adiabatic
(1/50 real time speed)

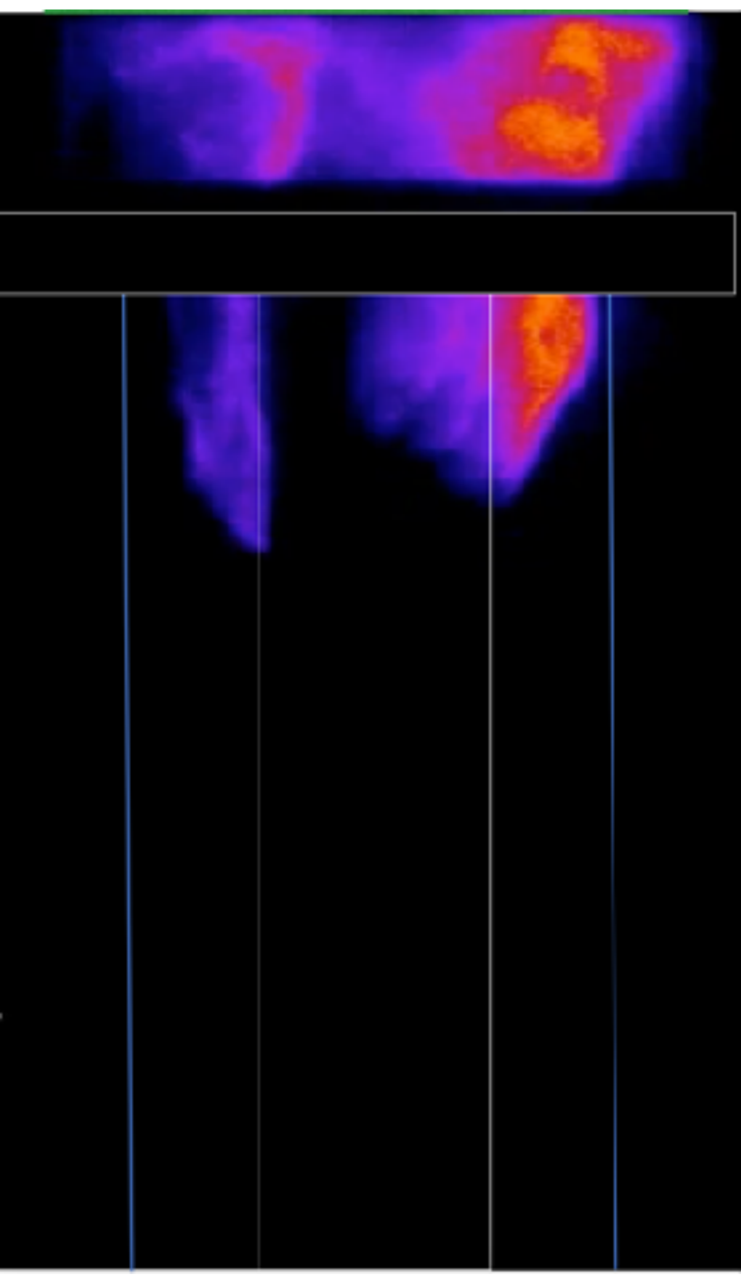


Non-adiabatic
(1/50 real time speed)

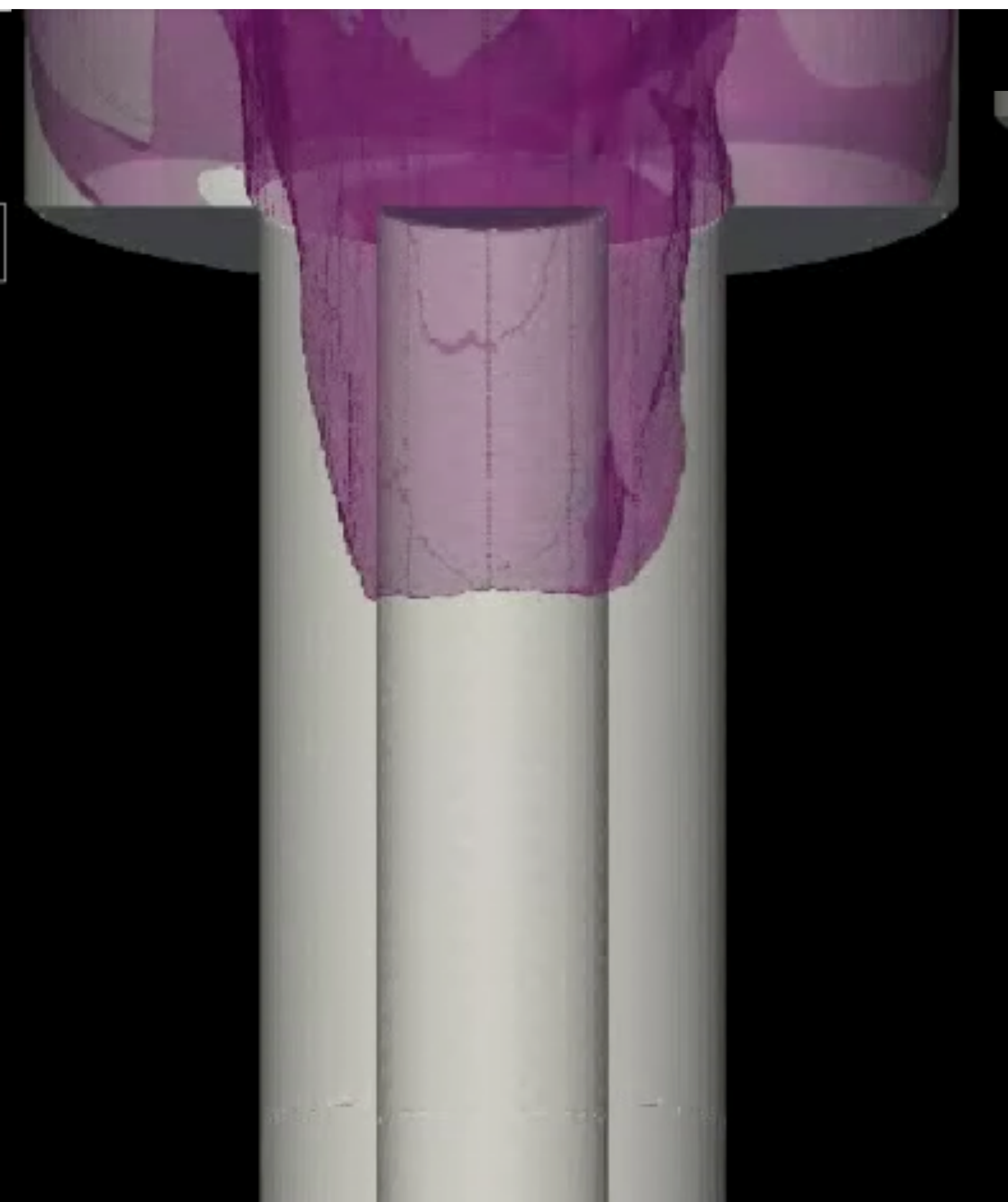


Non-adiabatic Reacting Case Study

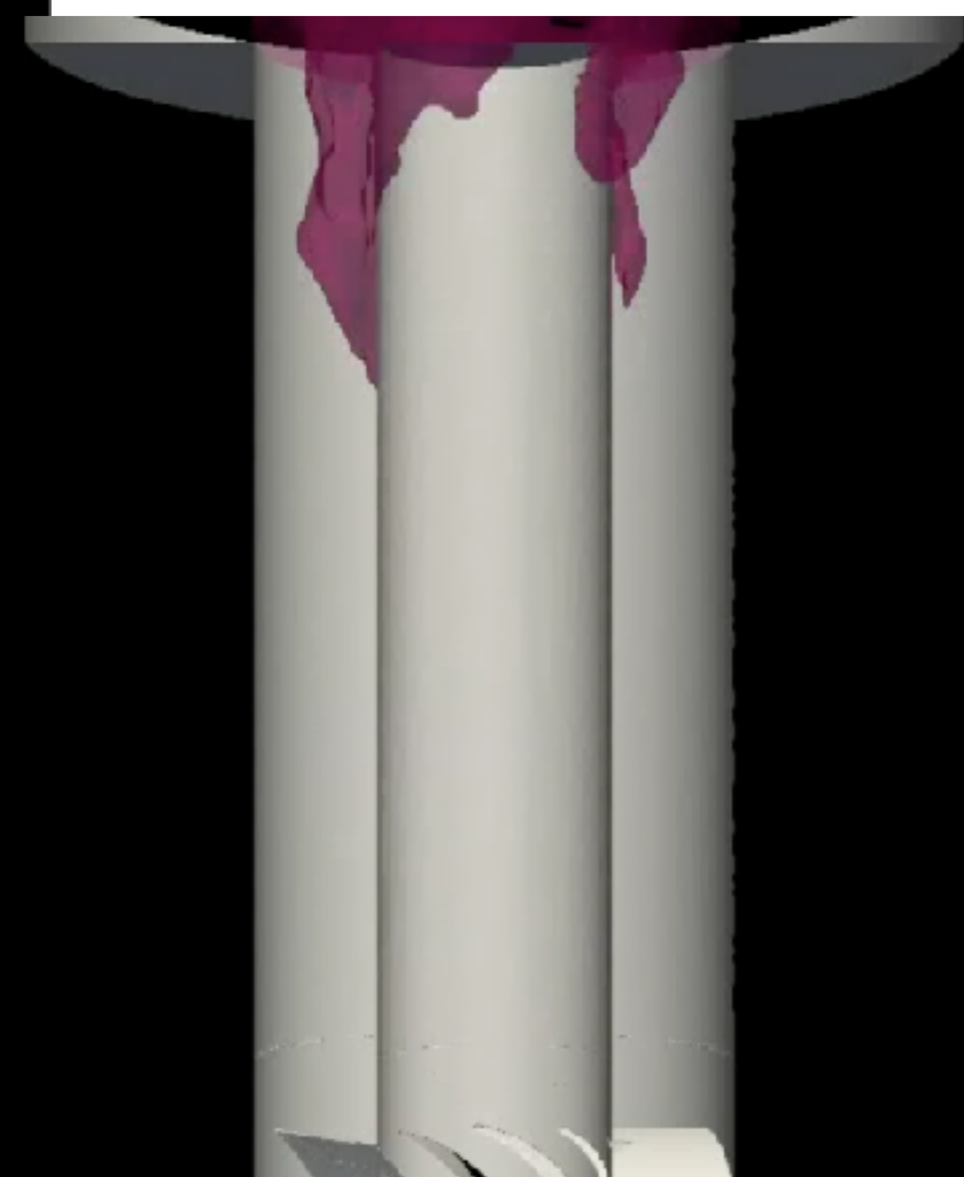
Chemiluminiescence



Adiabatic

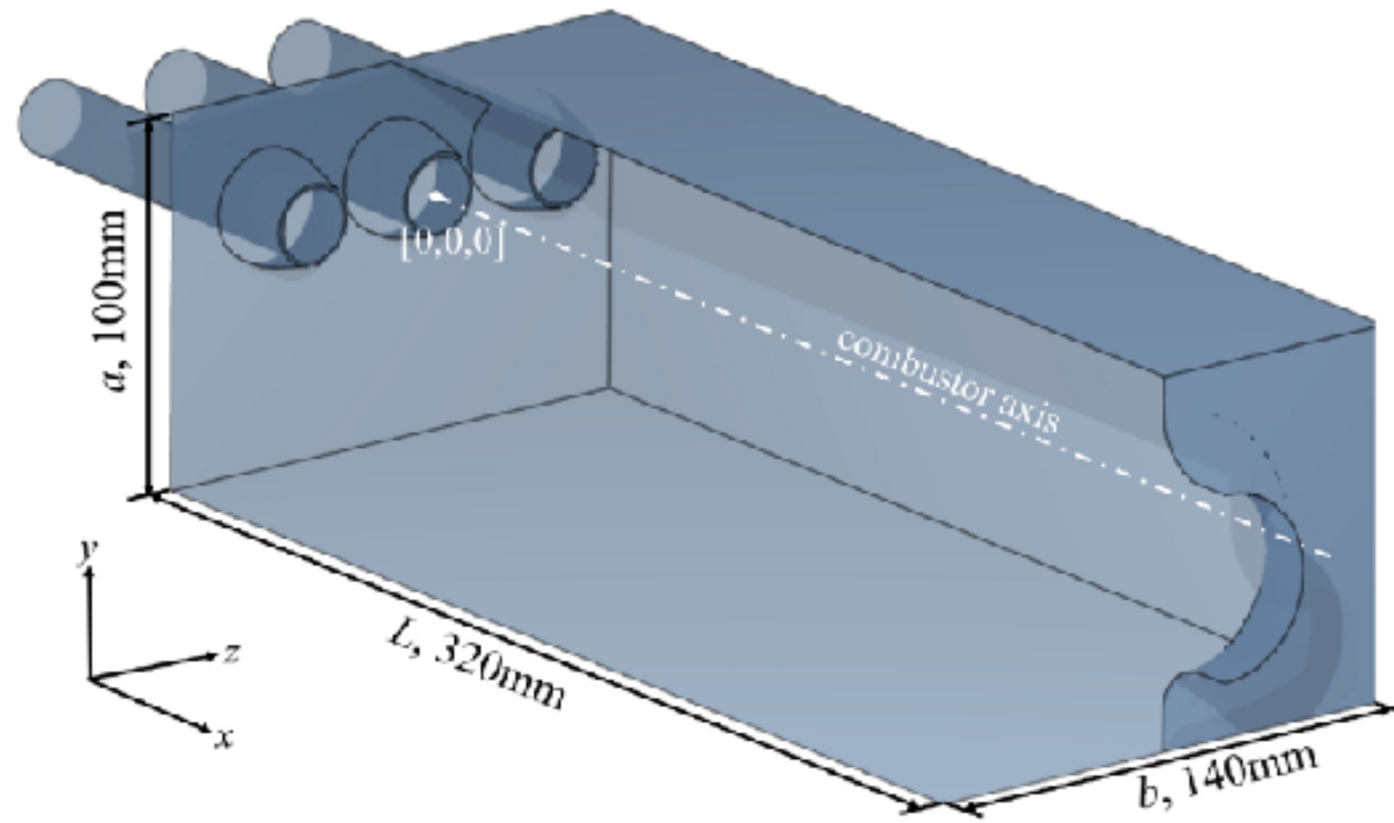


Non-adiabatic



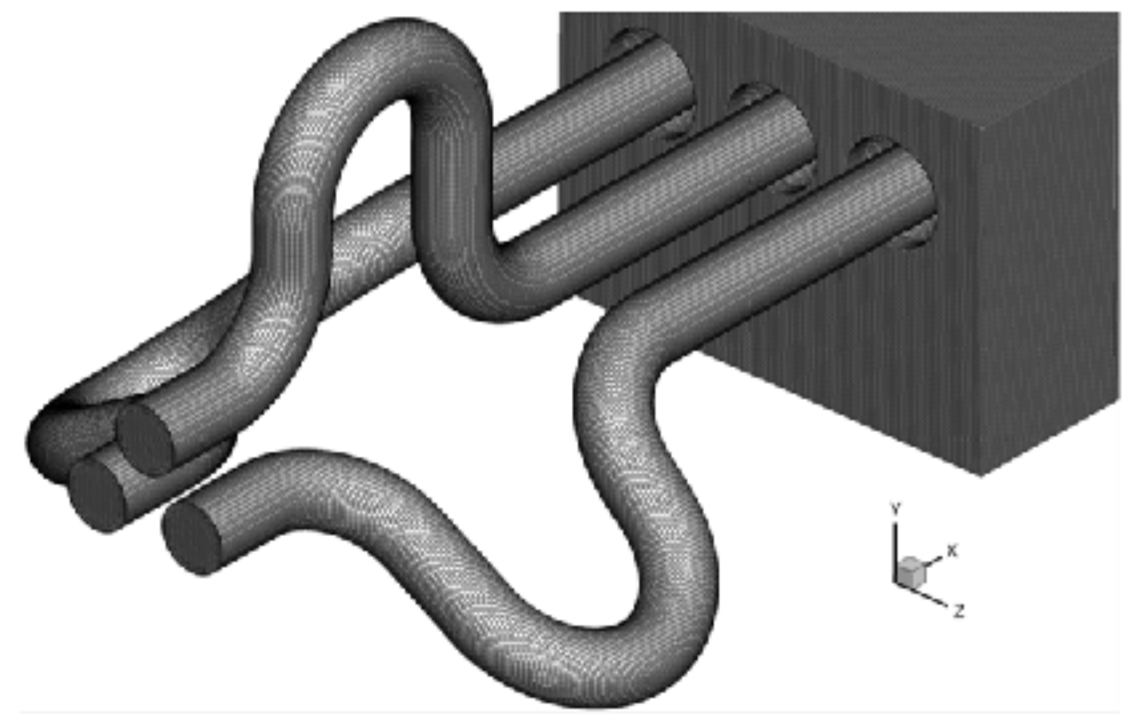
Lean Premixed Combustion at High Pressures

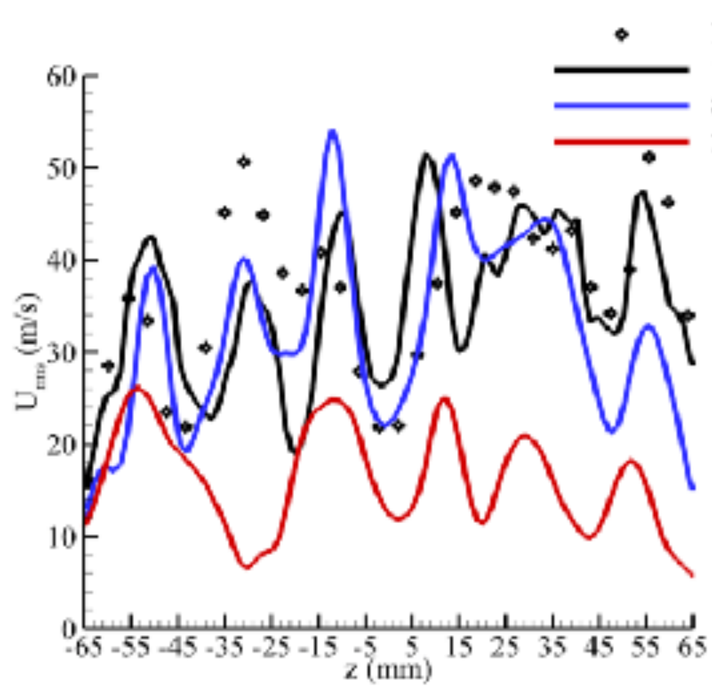
- **MILD combustion conditions**
  - ➡ High recirculation rate to maintain combustion
- **Asymmetric nozzles**
  - ➡ Recirculation predominantly b the nozzles
  - ➡ Very high jet velocities
- **Broad reaction zones**
  - ➡ Strain influenced
  - ➡ Large heat loss to walls
- **Methane or hydrogen as fuel**
- **Experimental data from DLR**

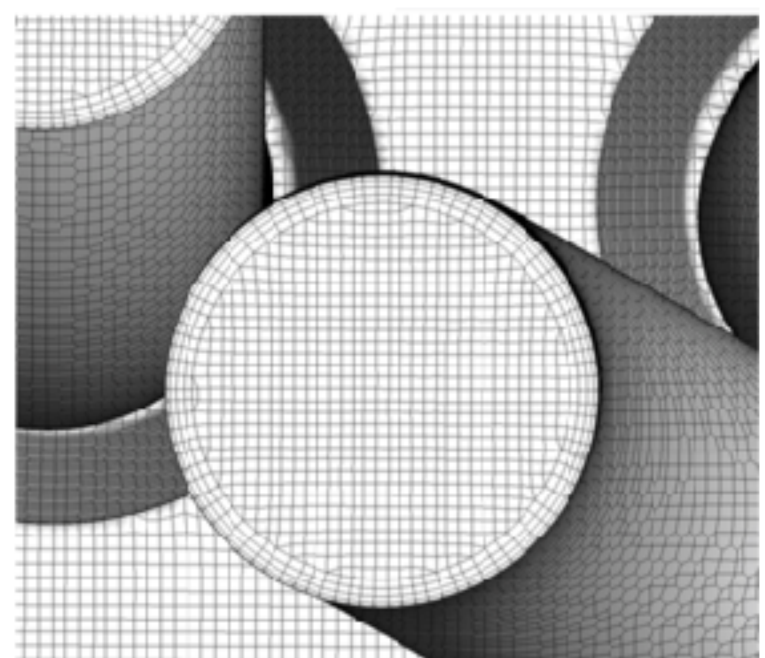


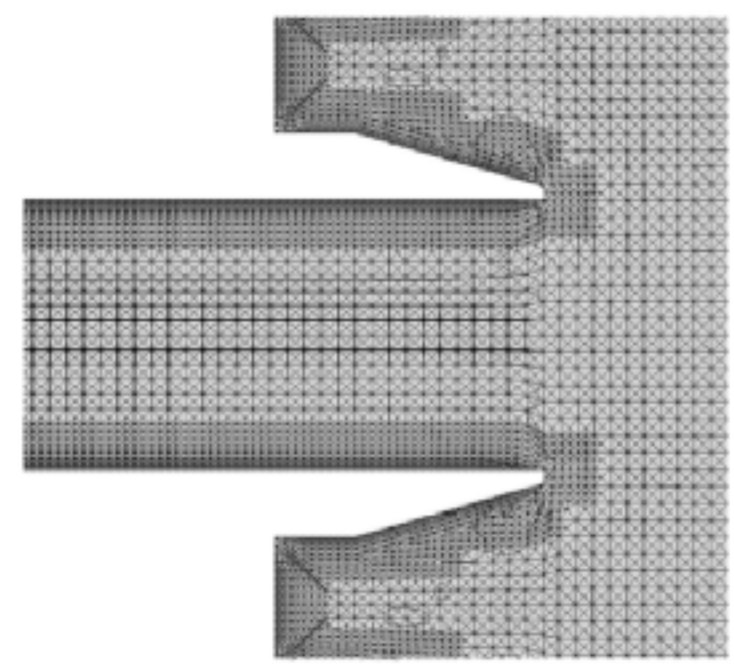
DLR 3-jet Case: Numerical details

- 8 M grid points in the flow DNS limit
- Dirichlet BC for velocity and progress variable
- Extended pipes at the inlet to generate turbulence
- Inlet velocity 120 m/s



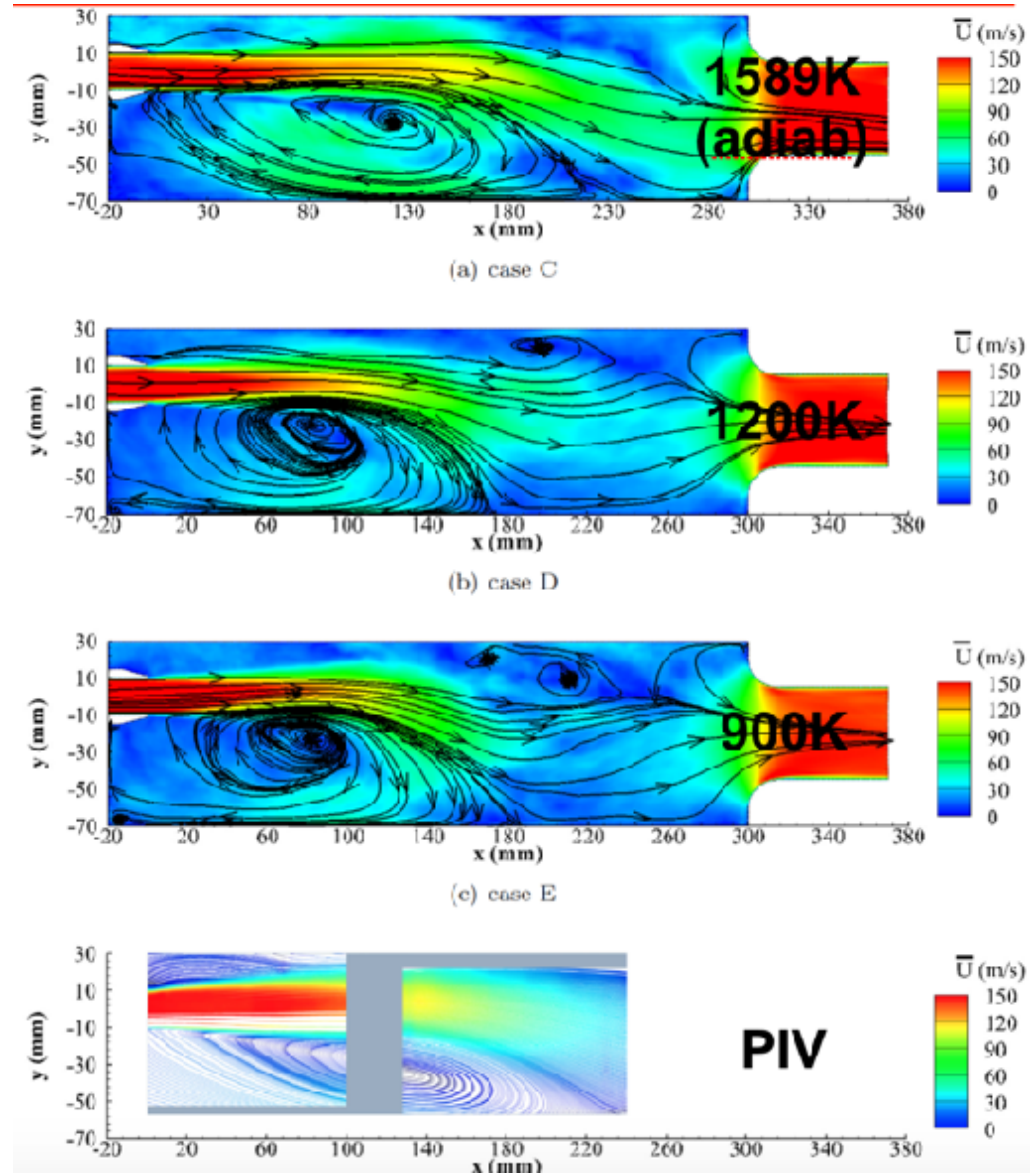






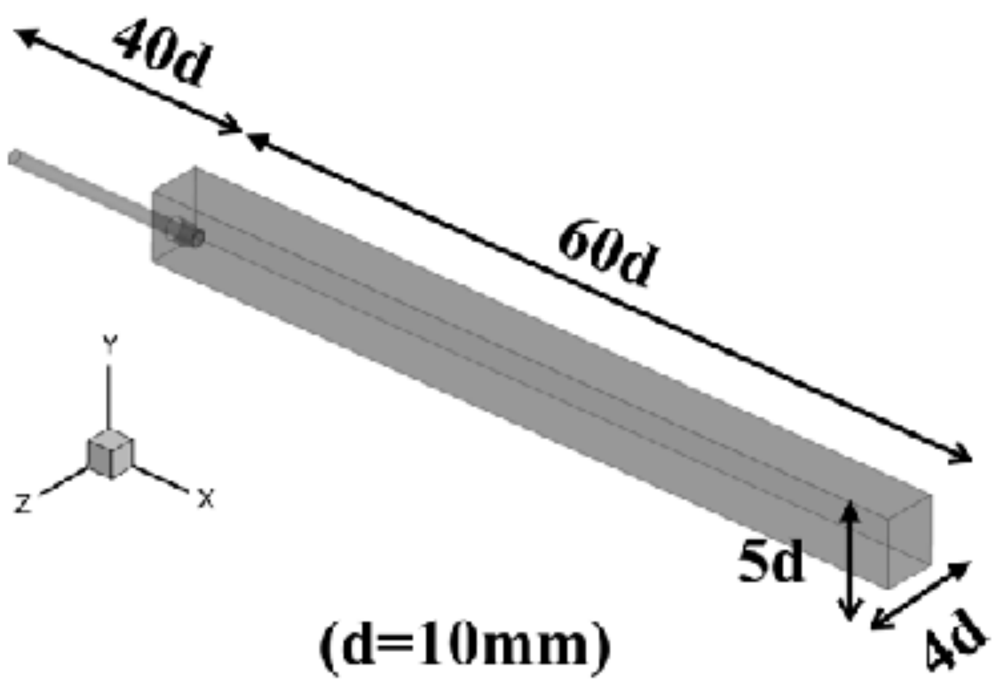
DLR 3-Jet Case - Heat Loss Effect

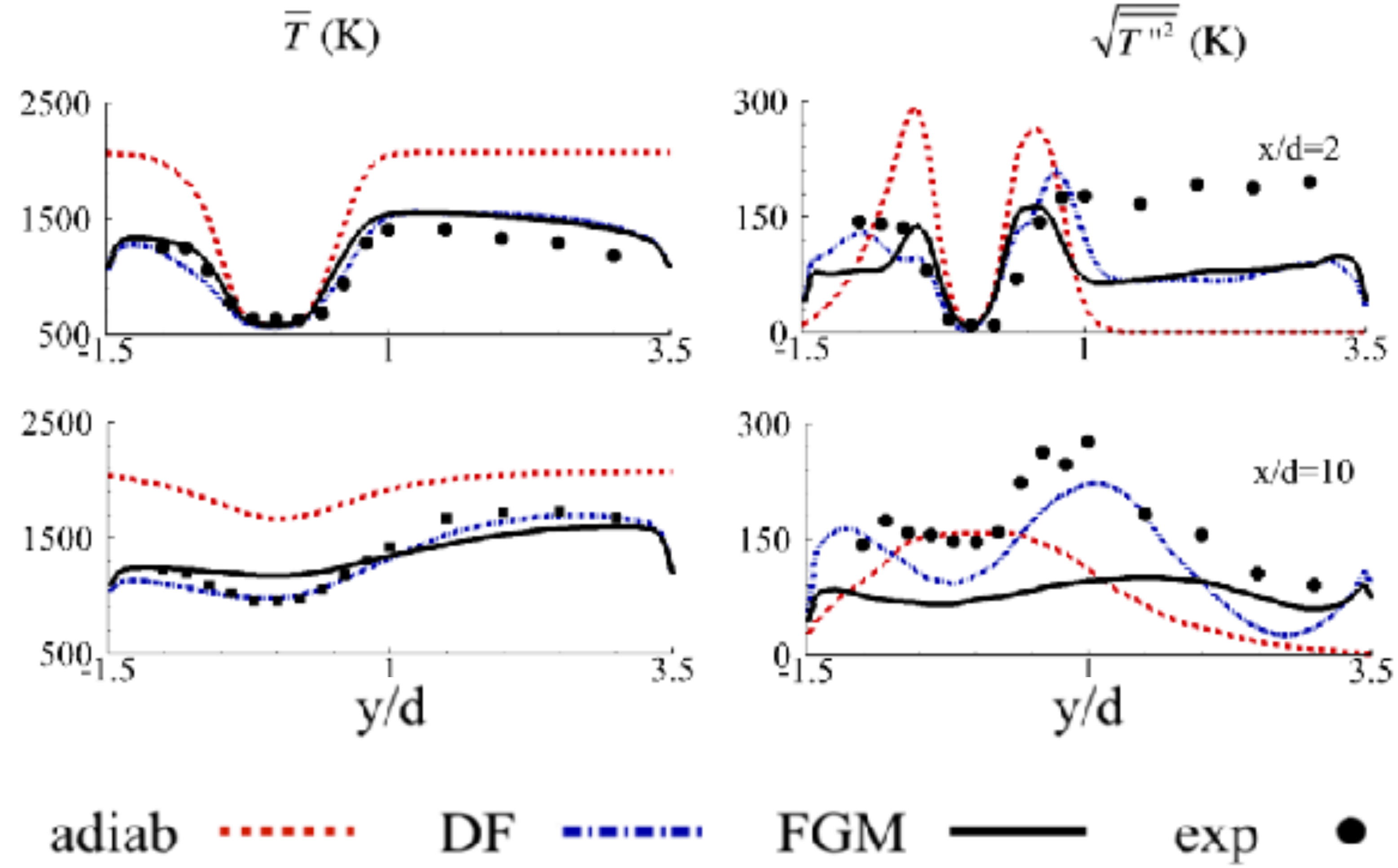
- **Wall temperature has significant effect on flow structure**
  - ➡ Higher heat loss leads to smaller recirculation zone
- **Simulations capture flow structure reasonably well**
  - ➡ Lack of adequate experimental data
  - ➡ Some issues with measurements noted



Validation - DLR 1-Jet Case

- **Modification of the 3-Jet case**
  - ➡ Single nozzle inflow

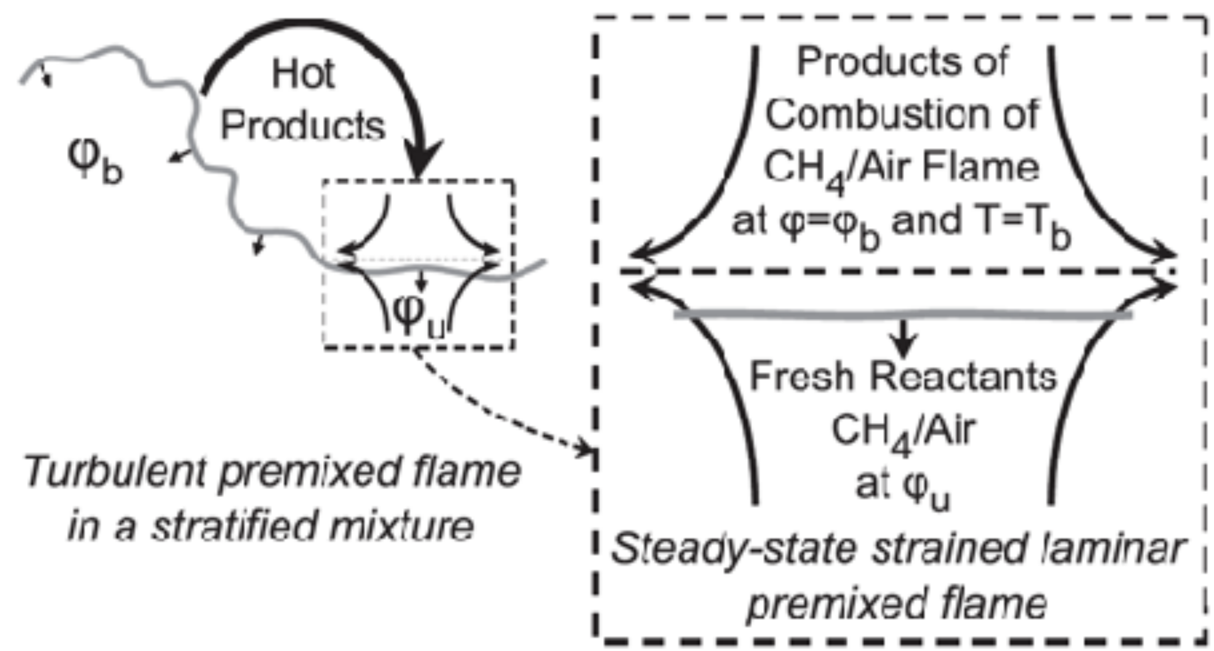




Preheat premixed methane-air:
Operating pressure: 1atm
Jet bulk velocity: 90m/s
Wall temp: 1000K
Equivalence ratio: 0.67

Effect of Strain

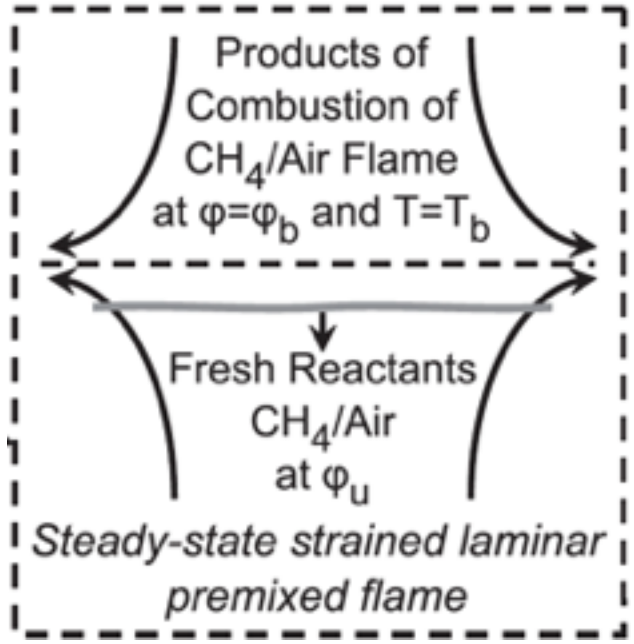
- **1D unstrained model based tabulation**
  - ➡ Overpredicts flame speeds even with heat loss
  - ➡ Combustion pushed towards thin reaction zone
- **Approach: Incorporate strain effects**
  - ➡ Consider opposed premixed flames
- **Strain effects can lead to varying mappings**

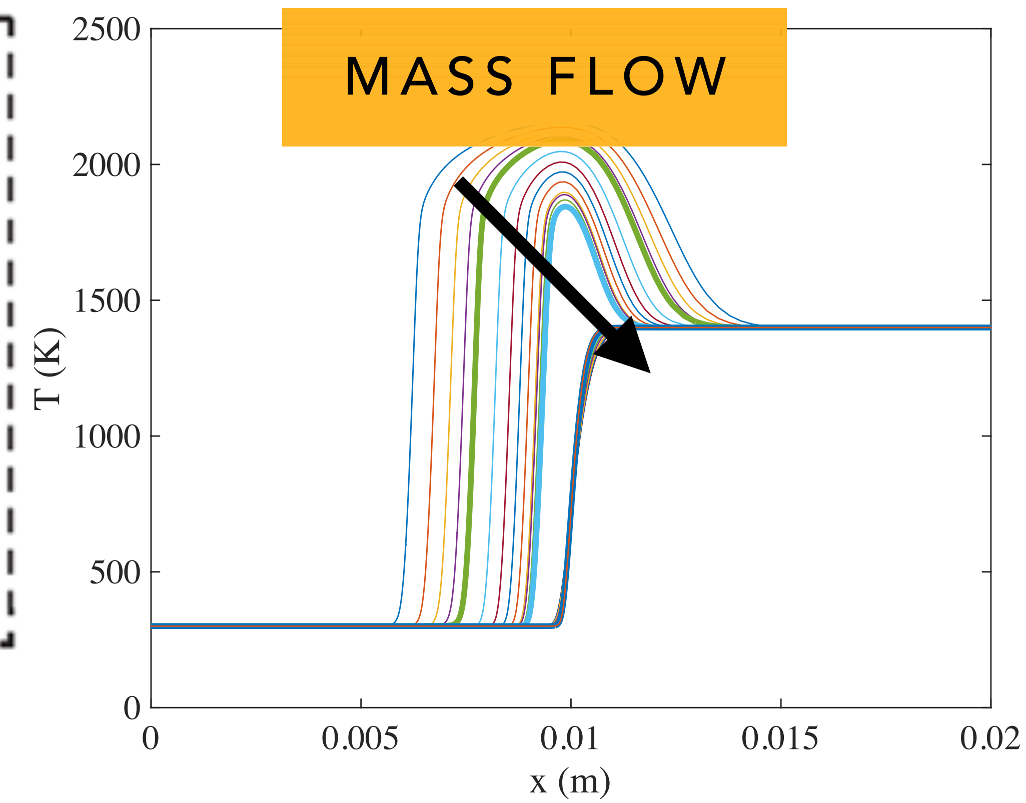


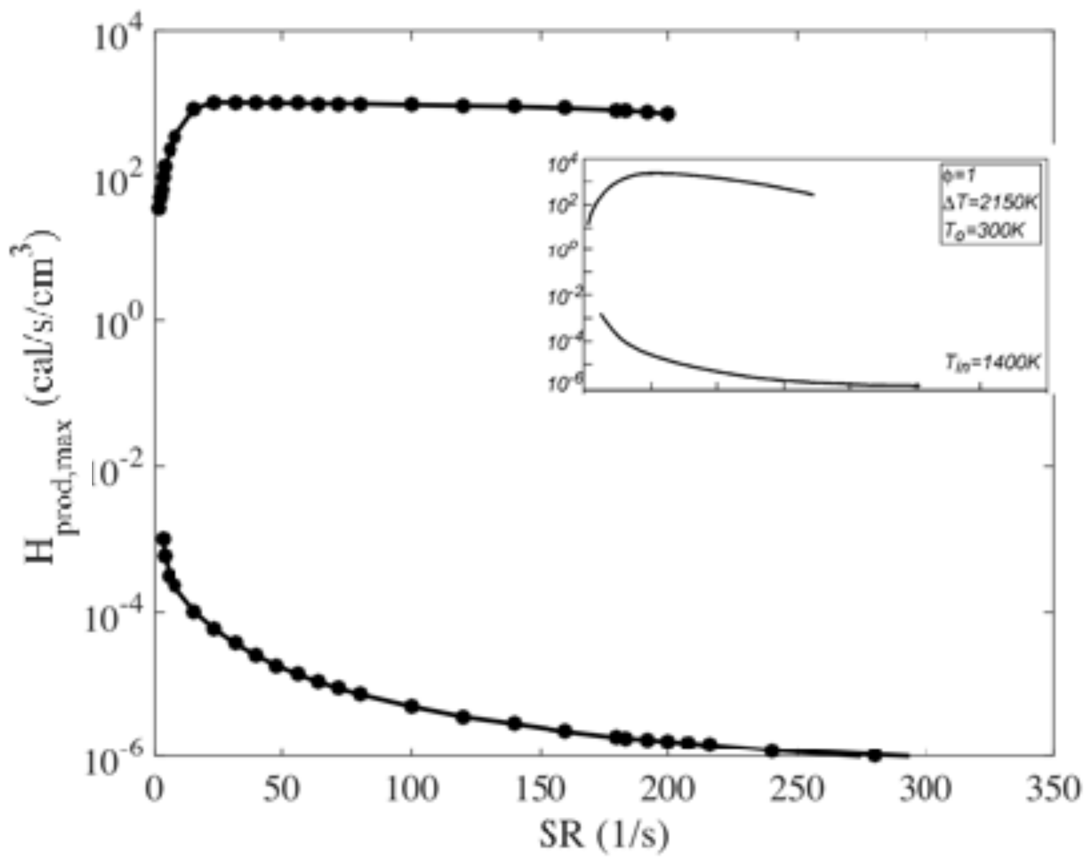
Obtained from B. Coriton, M. Smooke, A. Gomez (2016)

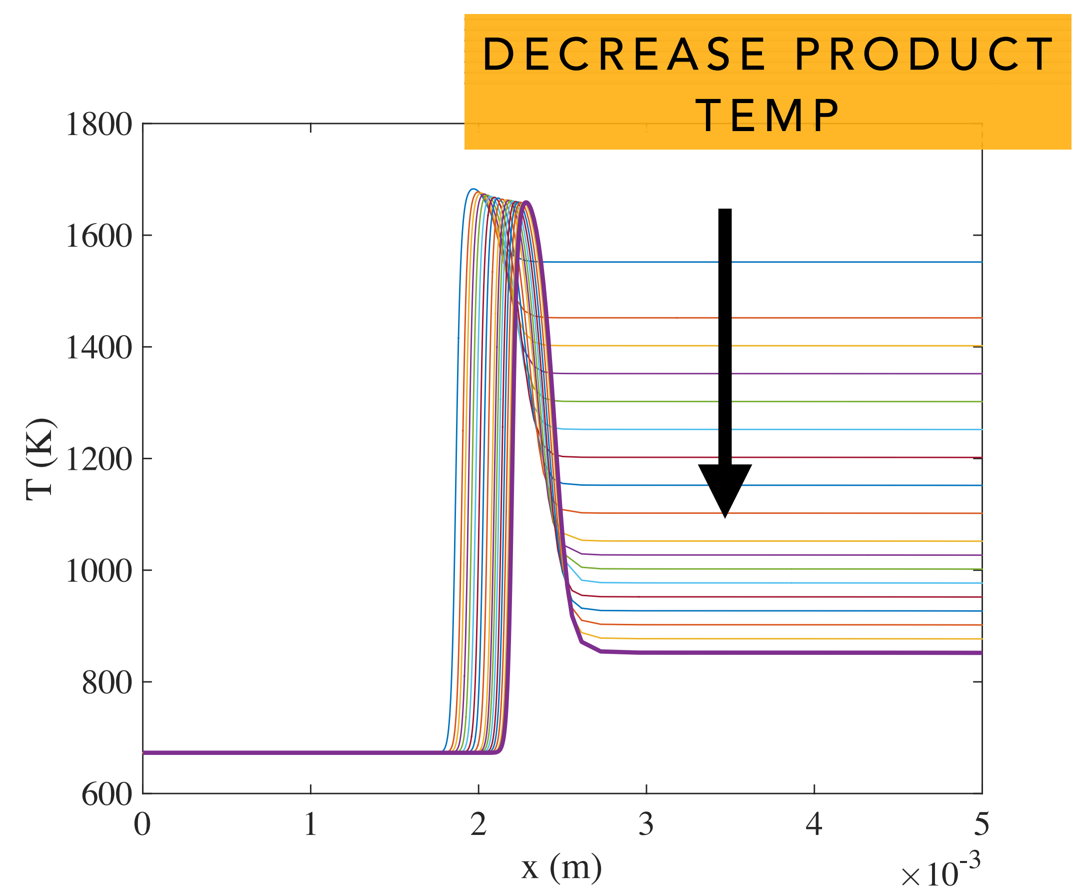
Counterflow Premixed Flame Tabulation

- **Flow solution known to have hysteresis effect**
- **Two control variables**
  - ➡ Mass flow (strain)
  - ➡ Product temperature (enthalpy)



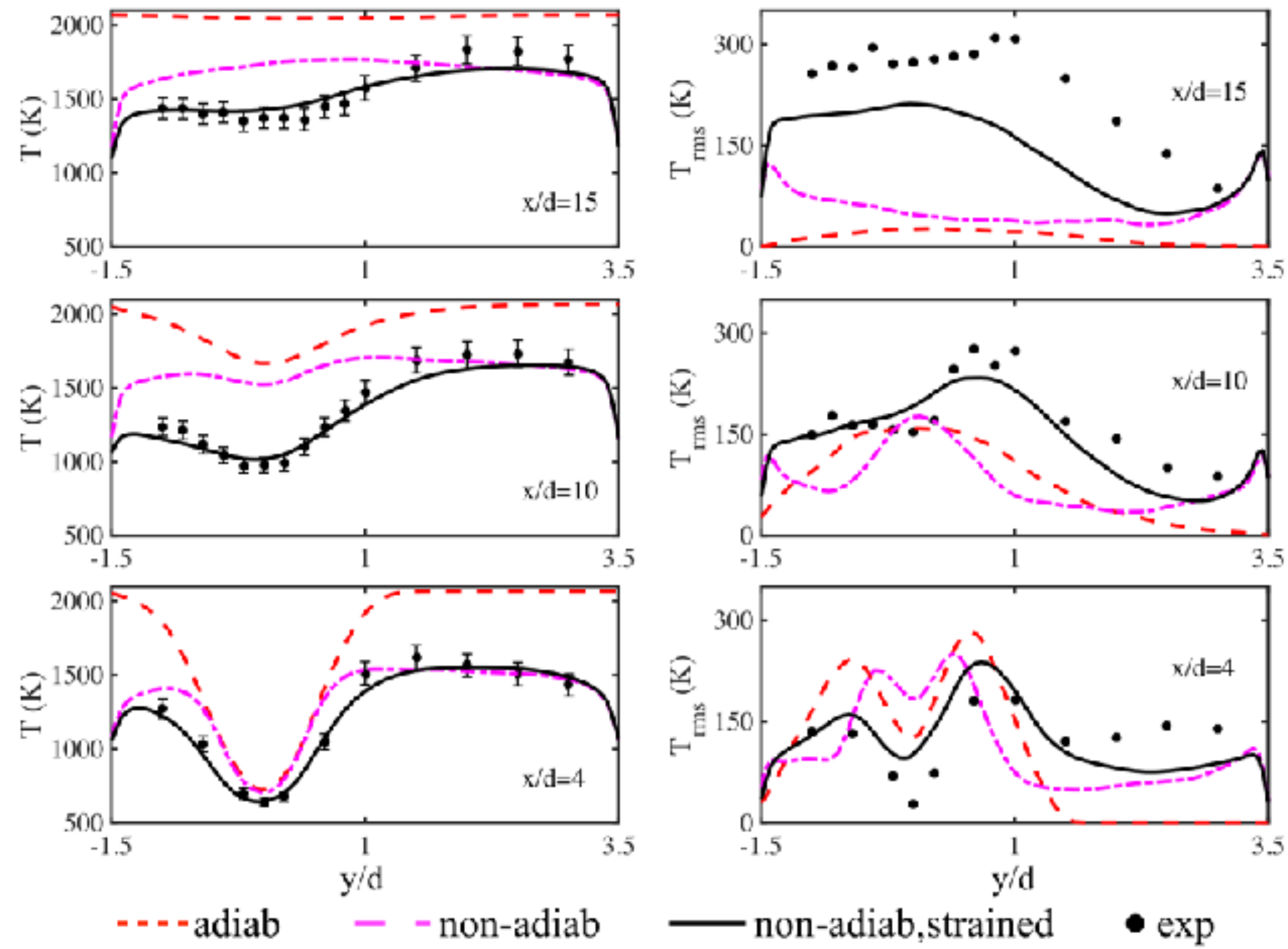






Obtained from M. de Joannon a, A. Matarazzo b, P. Sabia b, A. Cavaliere (2007)

Comparisons with Experimental Data



- **New flameout description highly accurate**
  - ➡ Captures temperature profiles throughout combustor

Summary of Findings

- **LES with modified flamelet closures**
  - ➡ Accurately predicts flashback processes
  - ➡ Captures MILD combustion processes
- **Solver plays a key role**
  - ➡ Non-dissipative numerics key to recovering turbulence characteristics
- **Strain rate seen as key parameter for modeling low equivalence ratio MILD combustion devices**
  - ➡ Non-adiabatic formulations necessary where heat loss to walls is important

Products of Research

- **Experimental database on boundary layer flashback**
  - ➡ Variety of fuels, equivalence ratios, pressures
  - ➡ Time-series of velocity and flame front data
- **General purpose LES solver for premixed and stratified flames**
  - ➡ OpenFOAM code base
  - ➡ All solvers available cooperative release
    - Already used by 6 universities and industrial partners
    - Models included in low-Mach number version of solvers
- **4 PhDs (2 still in progress) + several journal articles**