Flame Flashback in Hydrogen-rich Gas Turbines

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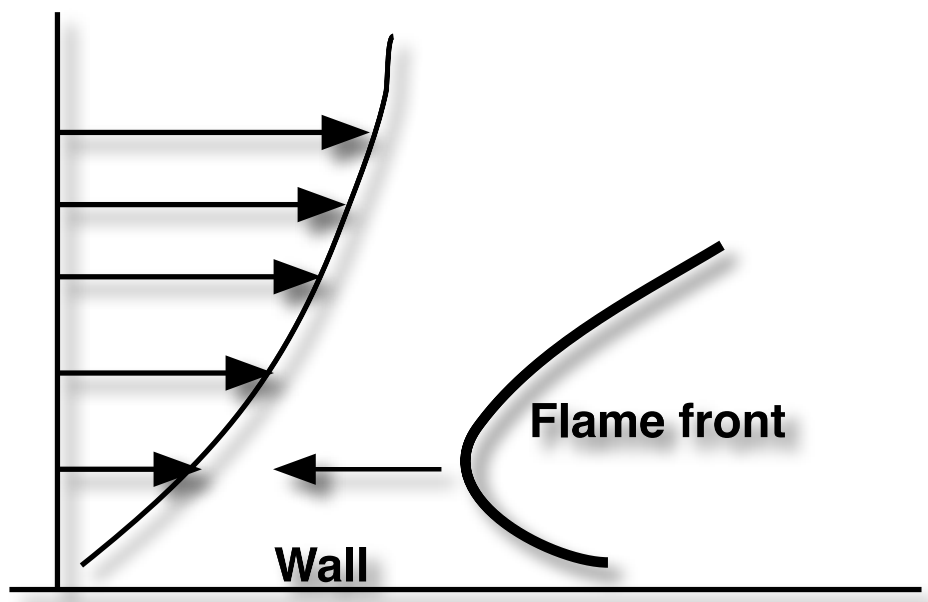
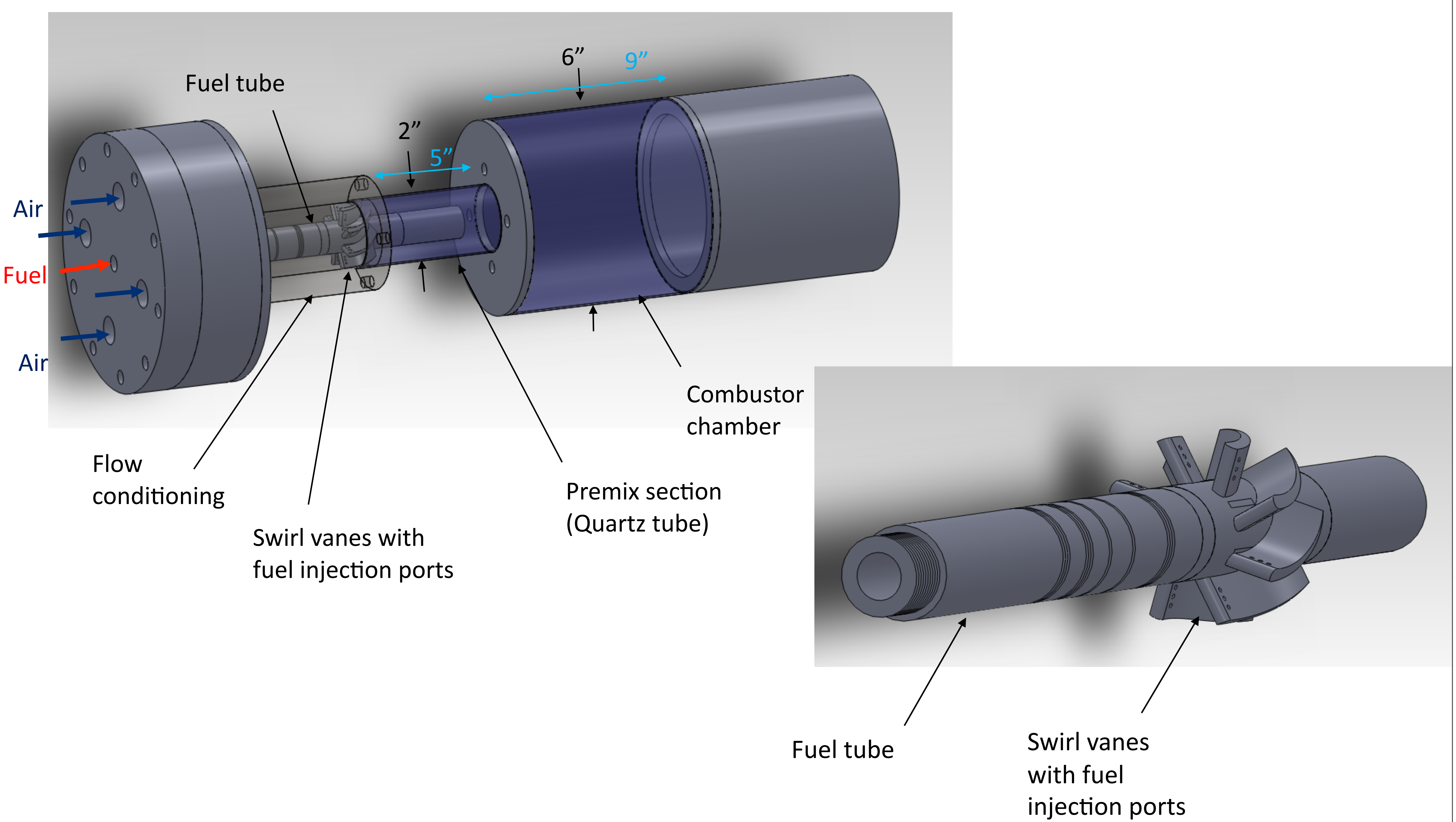
Background

- **Overarching goal: Understand flame flashback in hydrogen-rich gas turbines**
  - ➡ High pressure higher Reynolds number flow
  - ➡ Fuel stratification effects
- **Experimental program**
  - ➡ Conduct high pressure experiments in UT swirler configuration
  - ➡ Simultaneous PIV/PLIF measurements to characterize flame/boundary layer interaction
- **Computational program**
  - ➡ Develop models for predicting flashback in stratified flame configurations

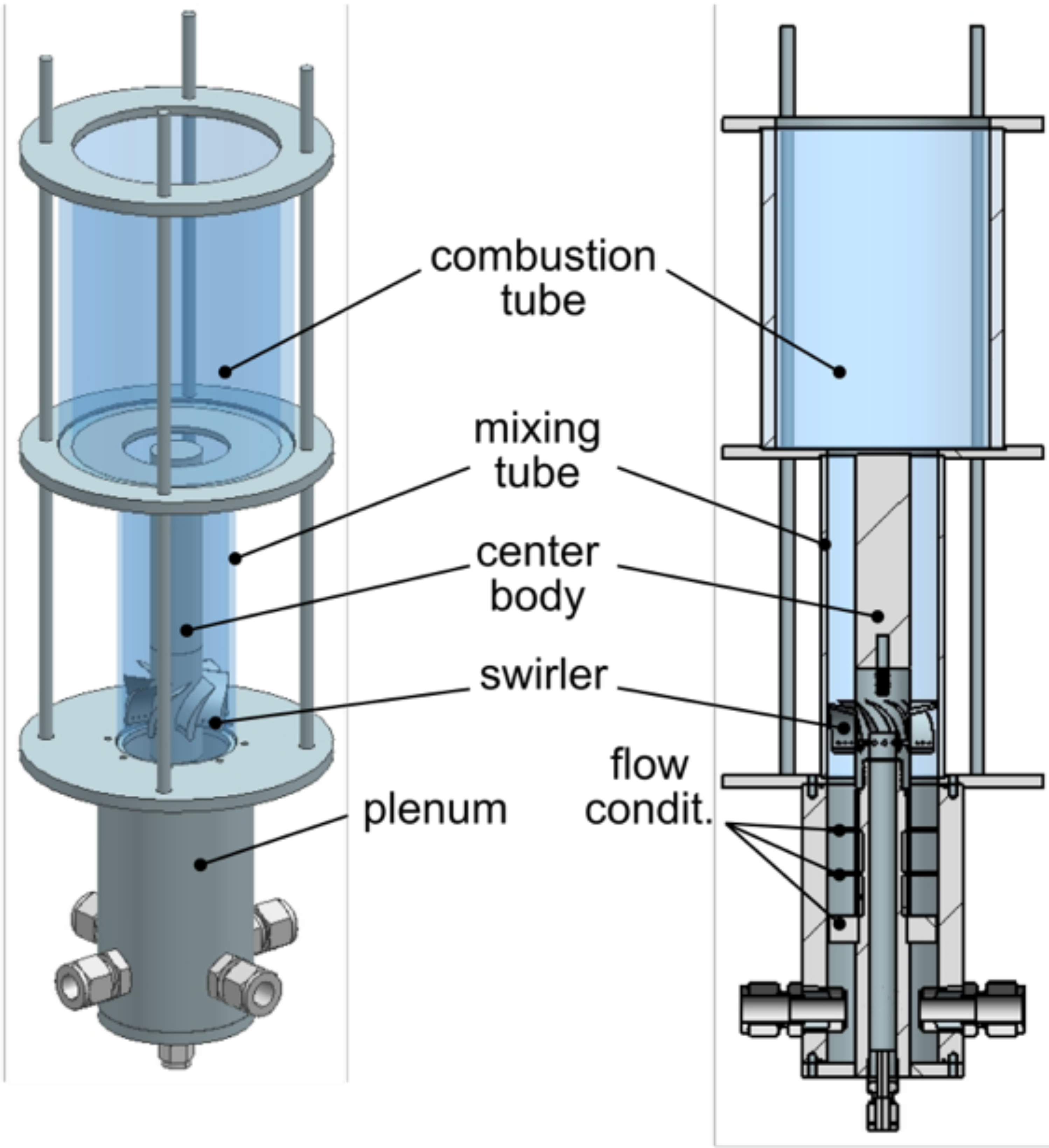


Target-based Flashback Modeling

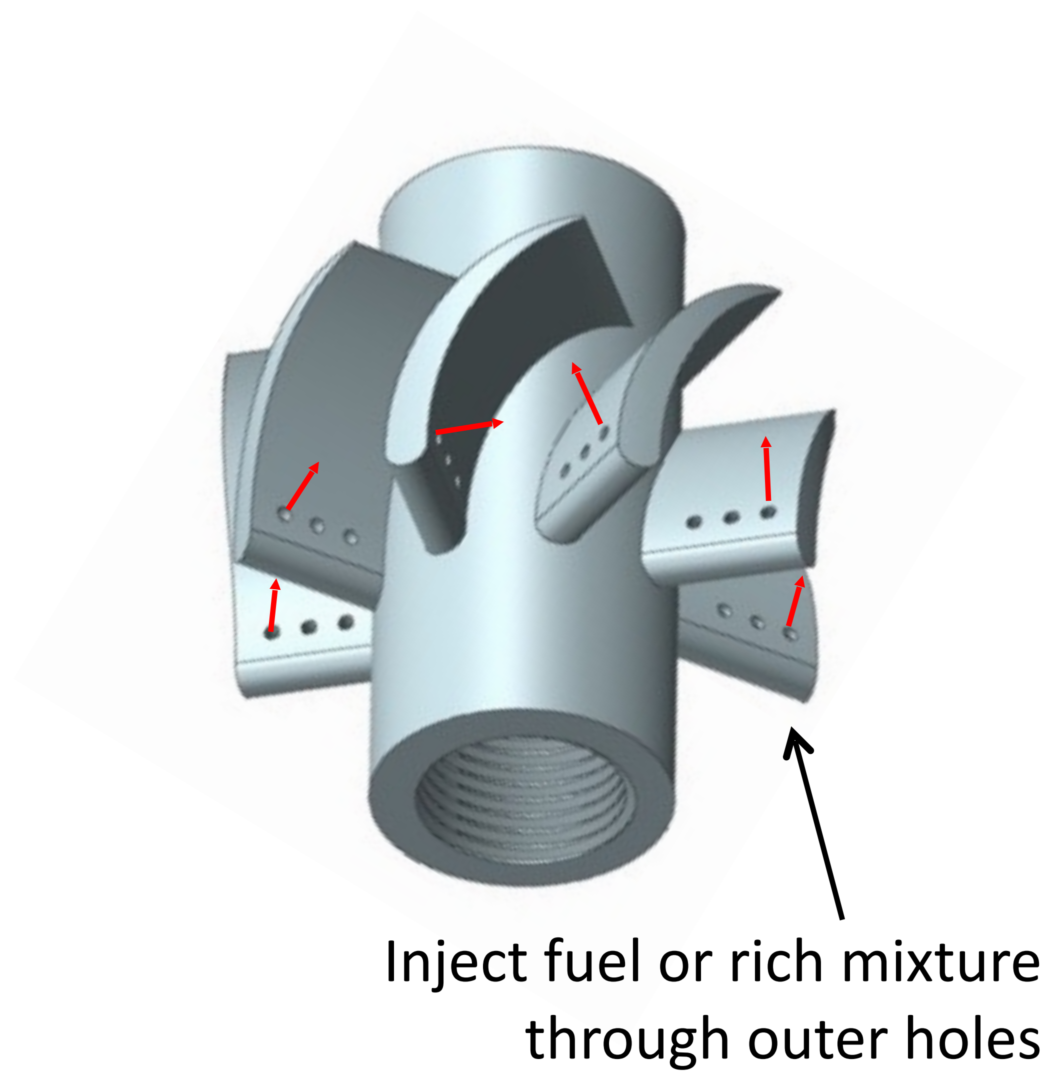
- **UT high-pressure swirl combustor**



Model swirl combustor



- Produce stratified flow by selective injection through swirl vanes



Summary of Results

- **High pressure experimental data**
  - ➡ 1-4 bar methane and methane/hydrogen experiments conducted
  - ➡ Focus on fuel stratification
- **Understanding model sensitivities**
  - ➡ Low-Ma vs compressible flow modeling
  - ➡ Effect of stratification on flame structure
  - ➡ Numerical modeling of flame structure propagation
  - ➡ Open source LES tool for gas turbines

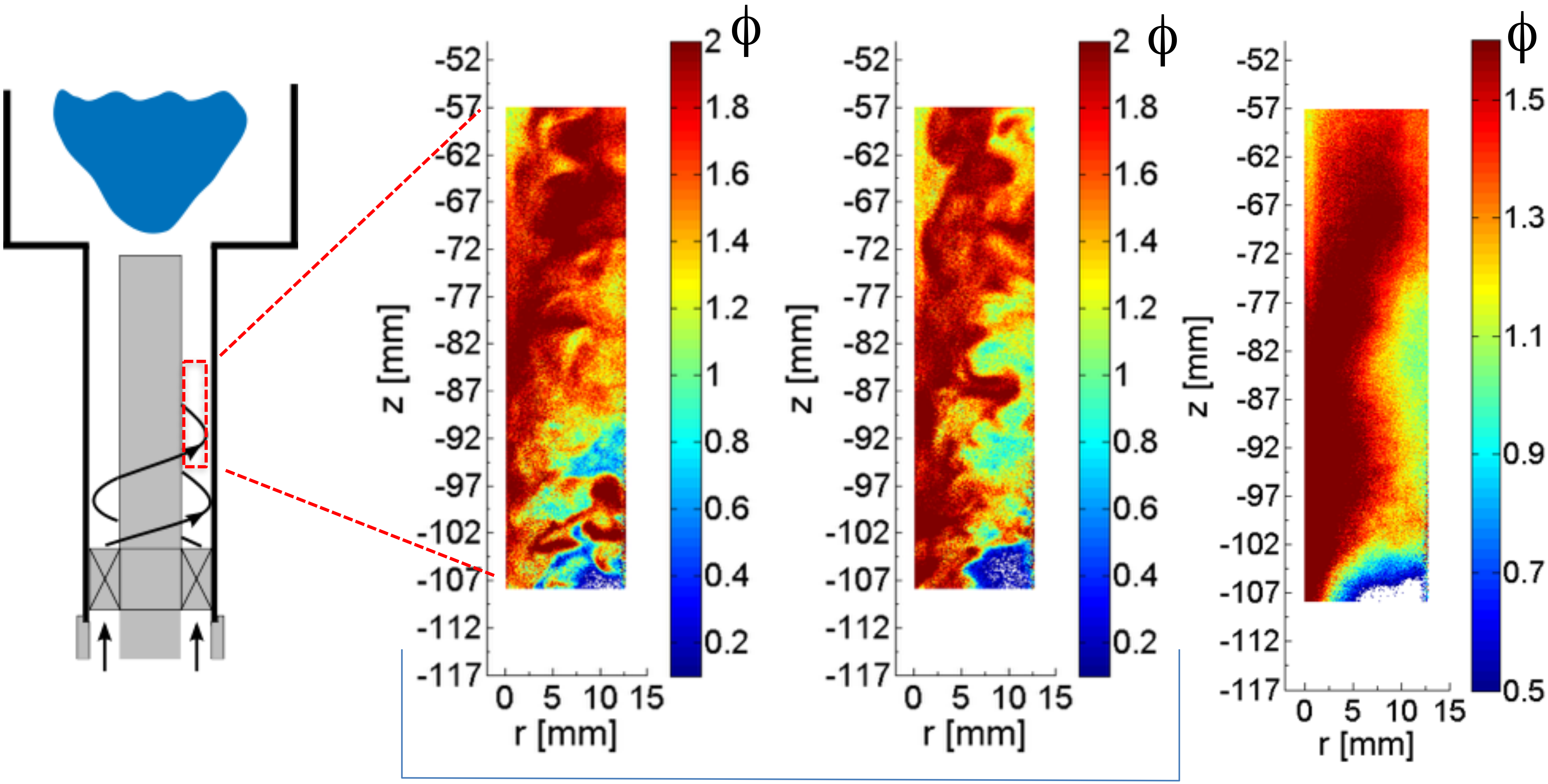
High-Pressure Combustion Facility

- Test stratification effects at elevated pressure
  - Up to 10 bar

- Swirl burner
- Concentric stratified flame burner

Acetone PLIF to assess stratification

- Acetone-CH_4 mixture injected through outer holes only
- Signals mapped to equivalence ratio

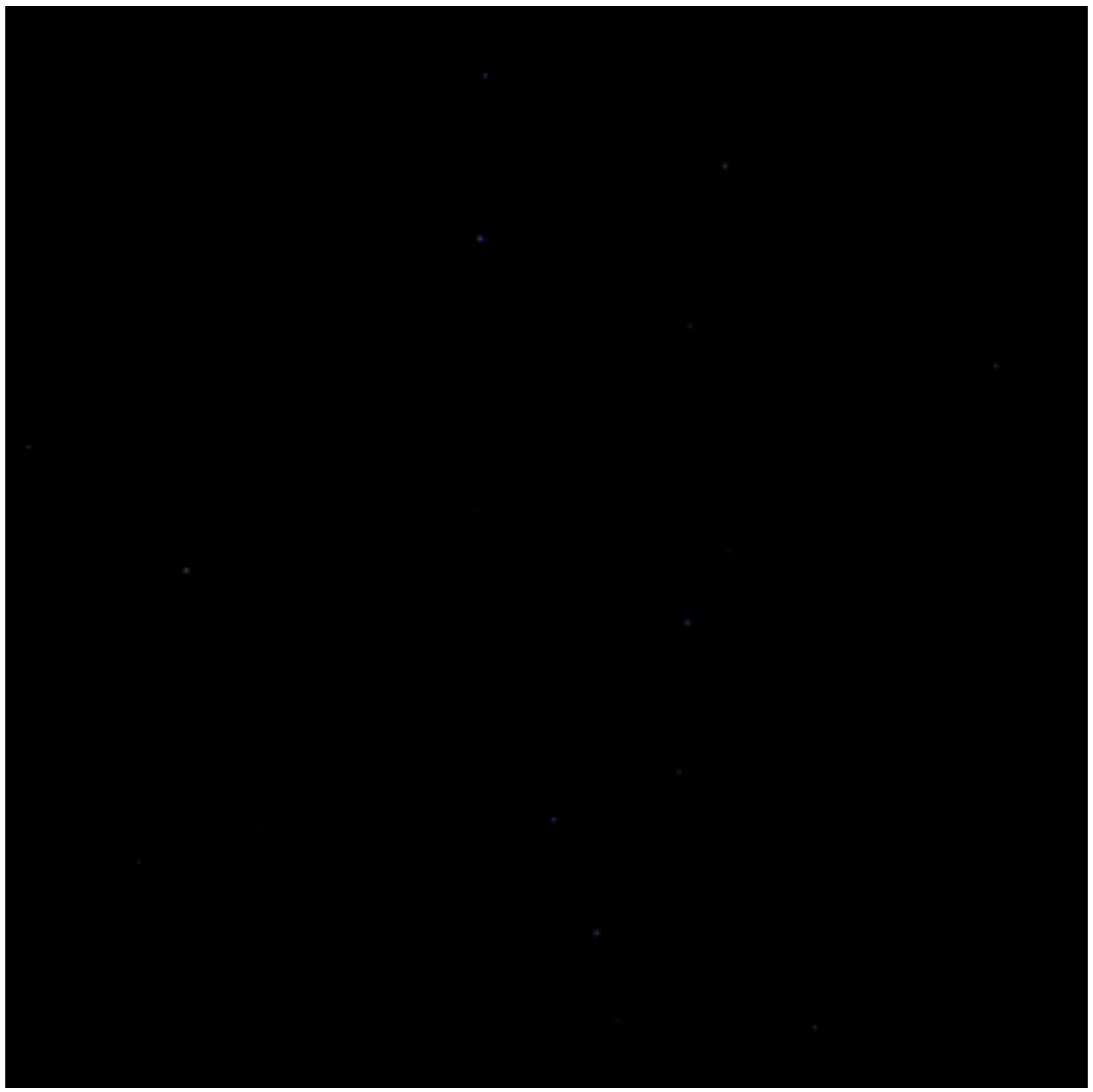


Instantaneous equivalence ratio

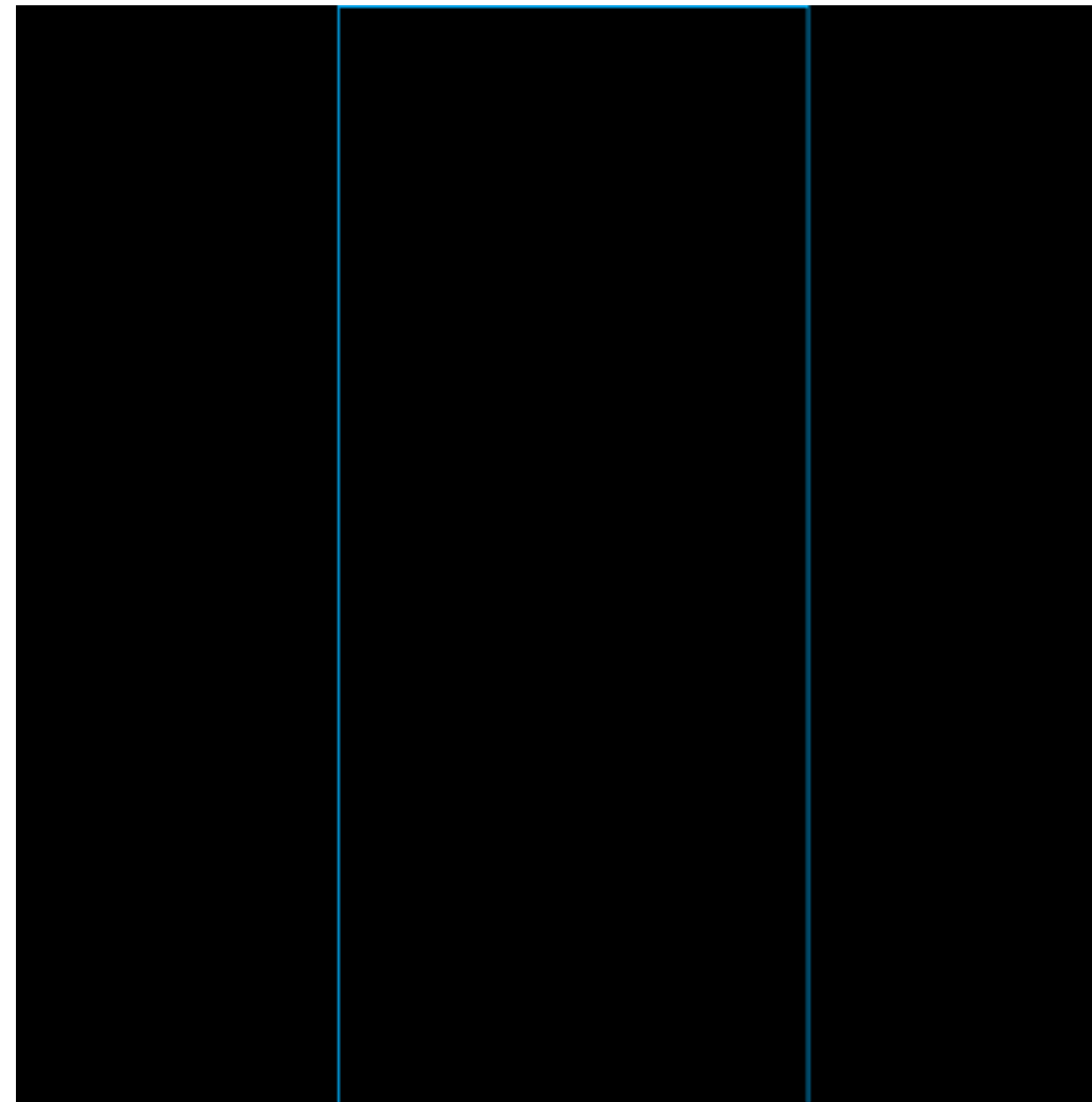
Mean

Effect of stratification on flashback

- Comparison of flashback with fully premixed and stratified reactants



Fully premixed



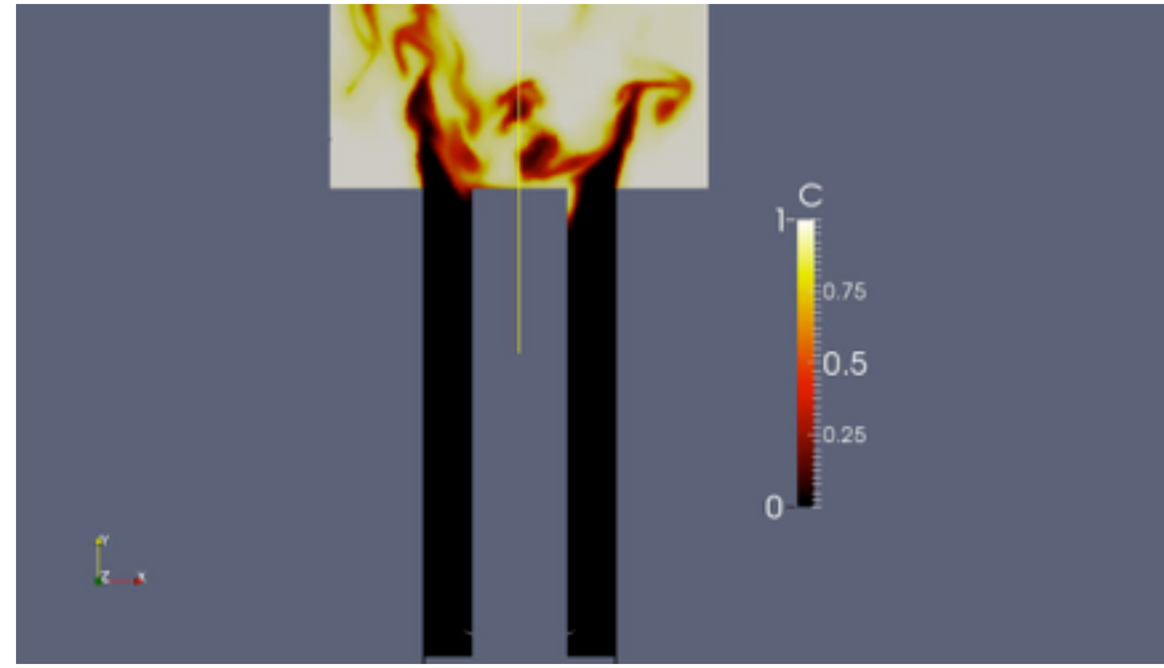
Stratified

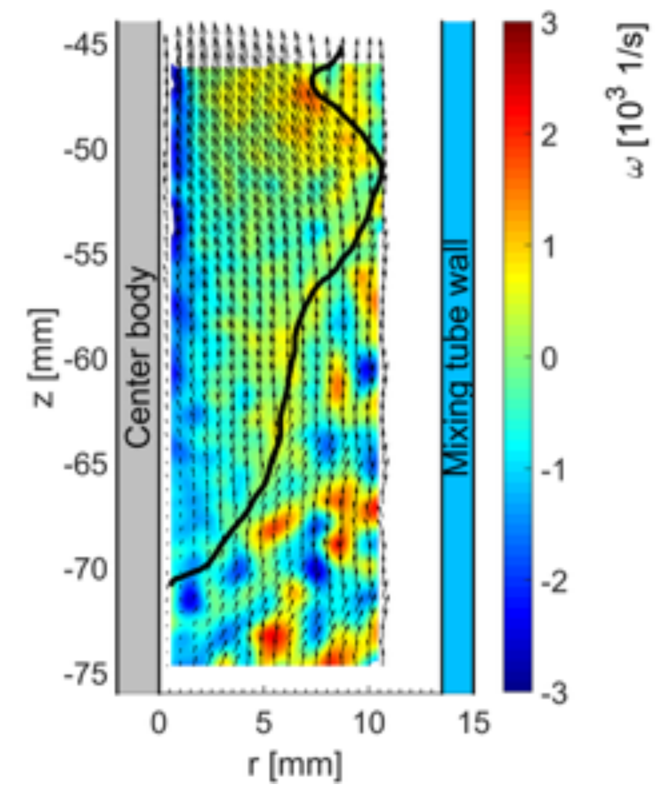
Summary of Results

- **High pressure experimental data**
  - ➡ 5 bar methane and methane/hydrogen experiments conducted
  - ➡ Focus on fuel stratification
- **Understanding model sensitivities**
  - ➡ Low-Ma vs compressible flow modeling
  - ➡ Effect of stratification on flame structure
  - ➡ Numerical modeling of flame structure propagation
  - ➡ Open source LES tool for gas turbines

Flow Laminarization

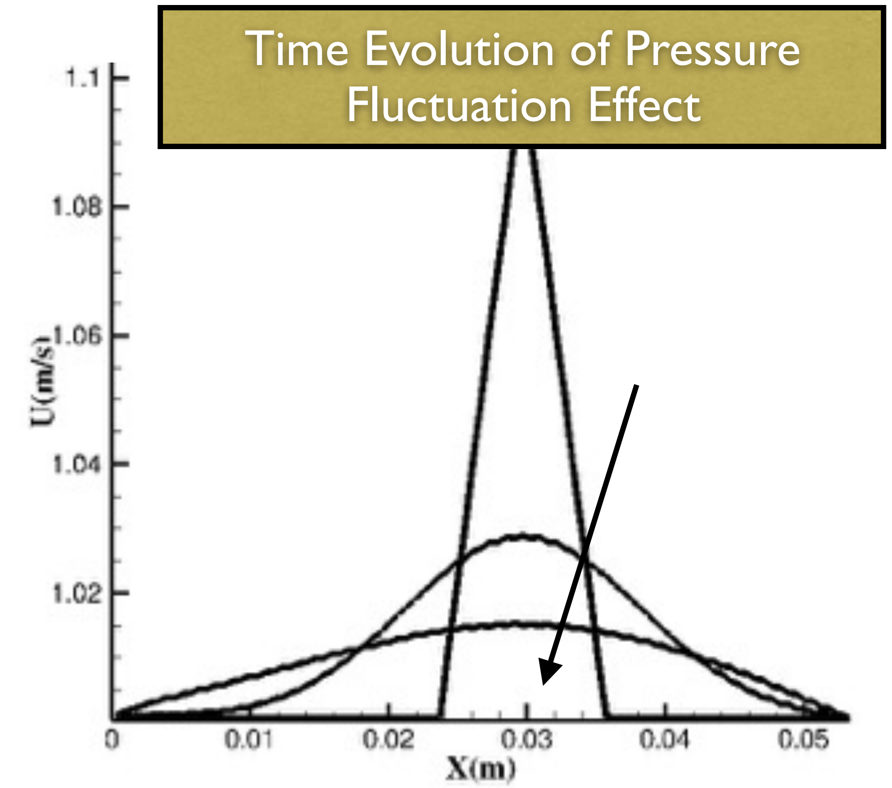
- **LES solvers based on low Mach number approximation**
  - ➡ Necessary for accelerated calculations in low speed flows
- **Flame propagation affects upstream turbulence more significantly than experiments**
  - ➡ Is there a finite propagation speed of pressure fluctuations?
  - ➡ Leads to laminarization of flow ahead of the flame
- **Are basic flow assumptions not valid in unsteady confined flame motions?**

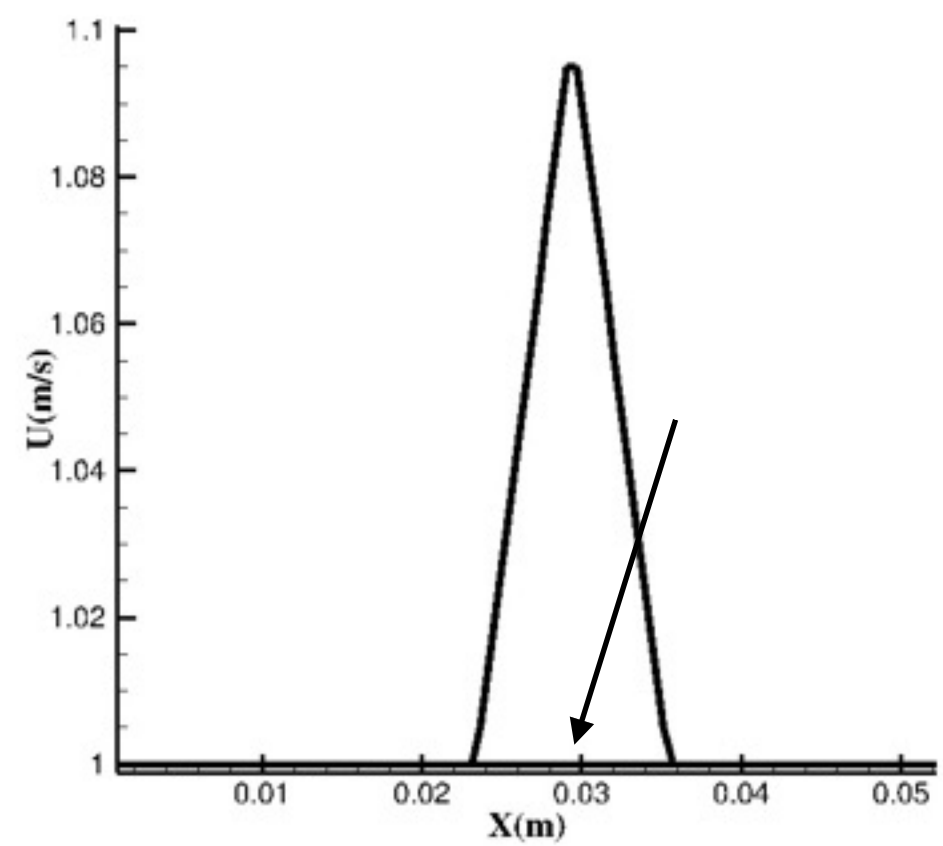




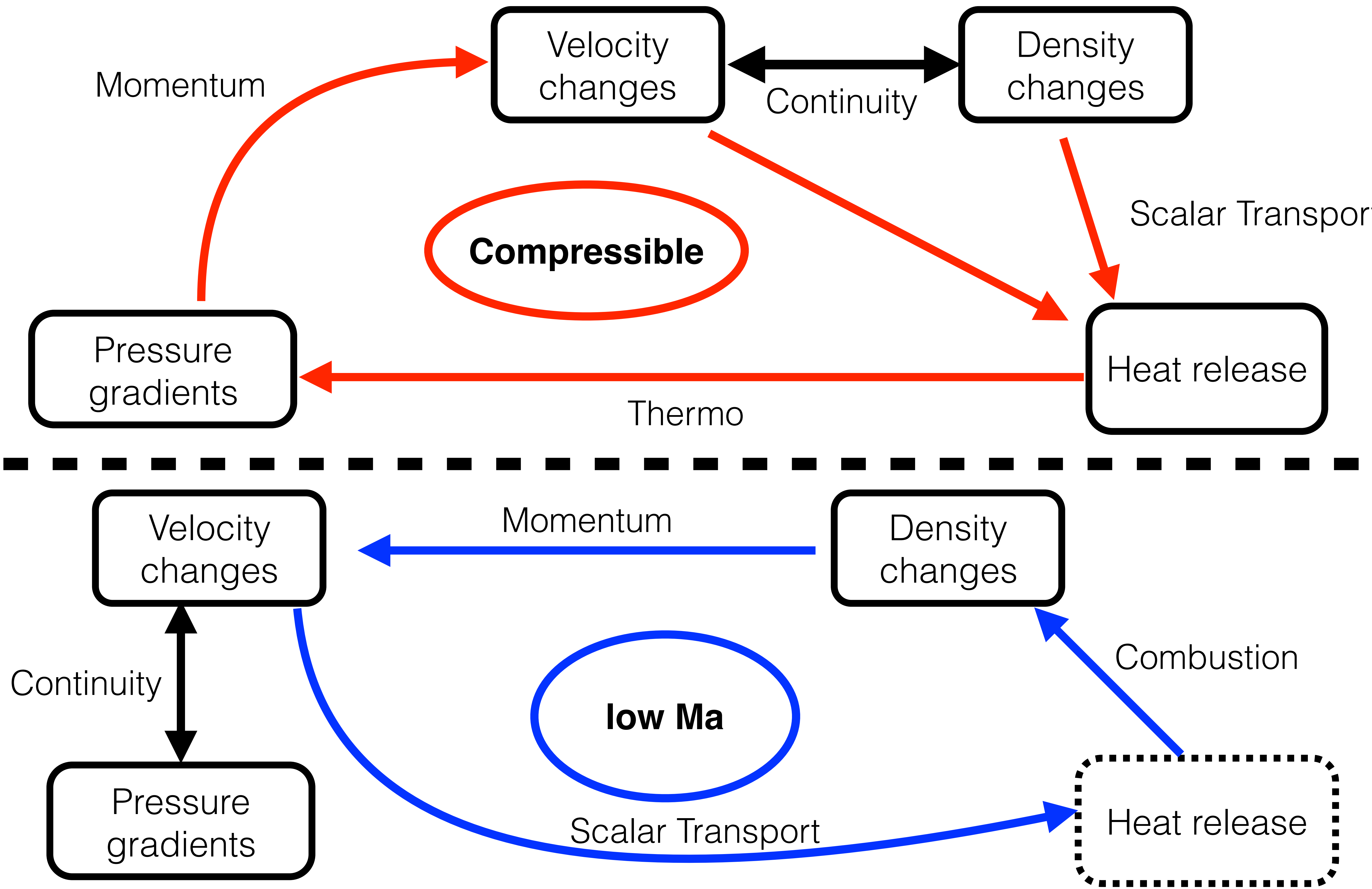
Effect of Compressibility on Transient Flows

- **Flow governing equations solved in two different ways**
  - ➡ Fully compressible formulation
    - No assumptions regarding compressibility
    - Time step limited by speed of sound
  - ➡ Low Mach number formulation
    - Assume pressure waves propagate at infinite speed
    - Time step limited by local fluid velocity
      - Ideal for slow but variable density flows
- **Is low Ma assumption valid for transient flashback events?**
  - ➡ Pressure gradients propagate at finite speed changing local flow structure





Compressible vs Low Mach Number Solver



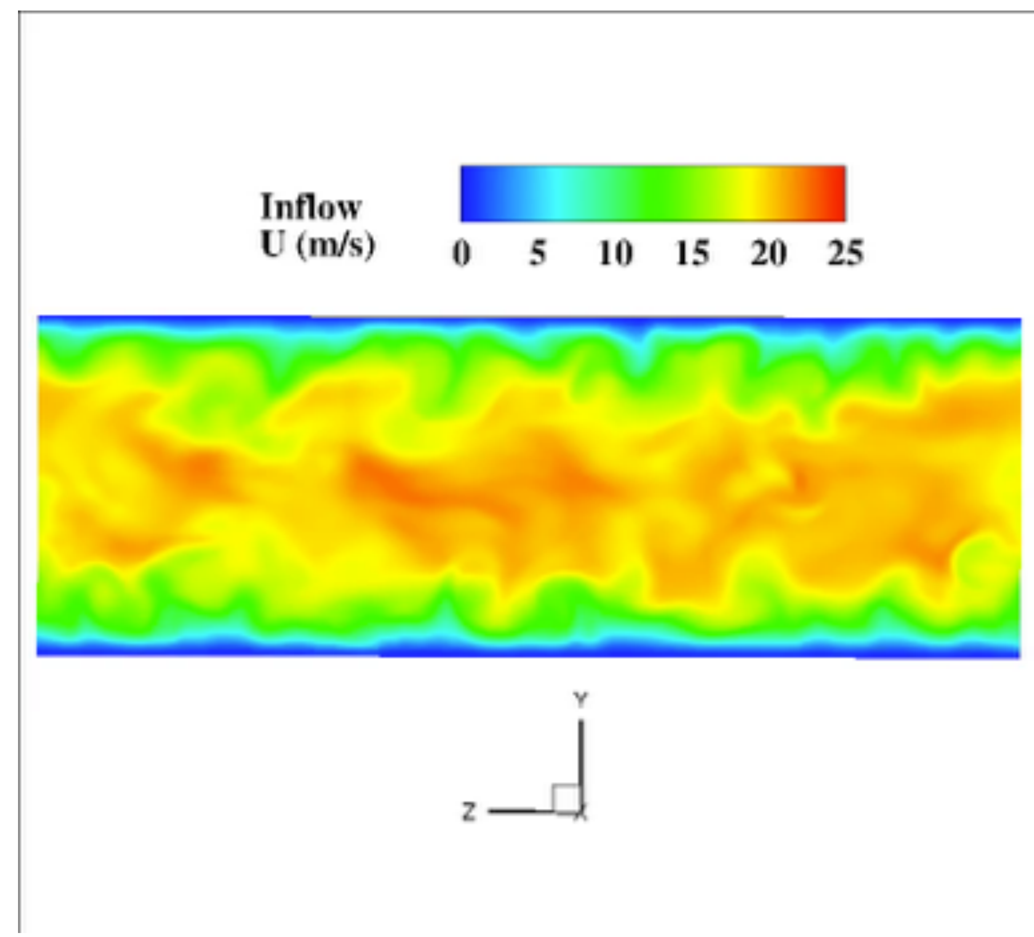
Numerical procedure

Compressible	Low Ma
5th order WENO scheme for convection	6th order central scheme for convection
6th order central scheme for diffusion	6th order central scheme for diffusion
BQUICK for scalar	BQUICK for scalar

- **LES with dynamic Smagorinsky model**

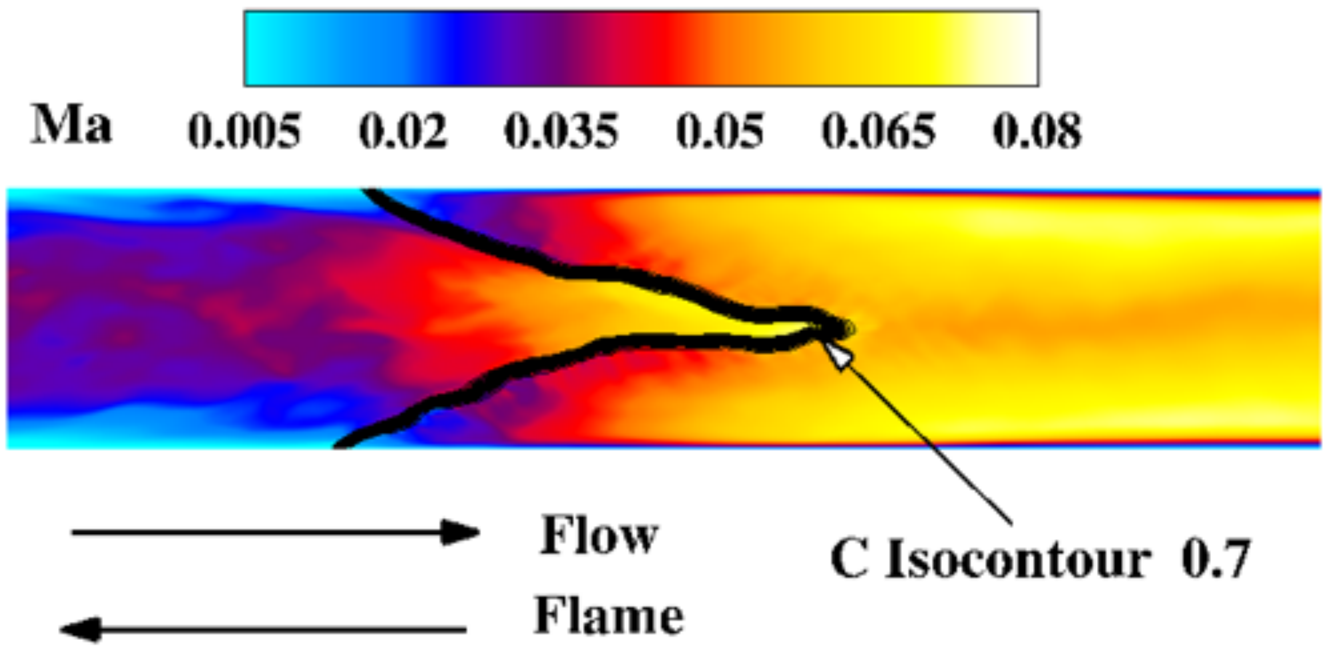
$$\Delta_{LES} = 0.1 \text{ mm}$$

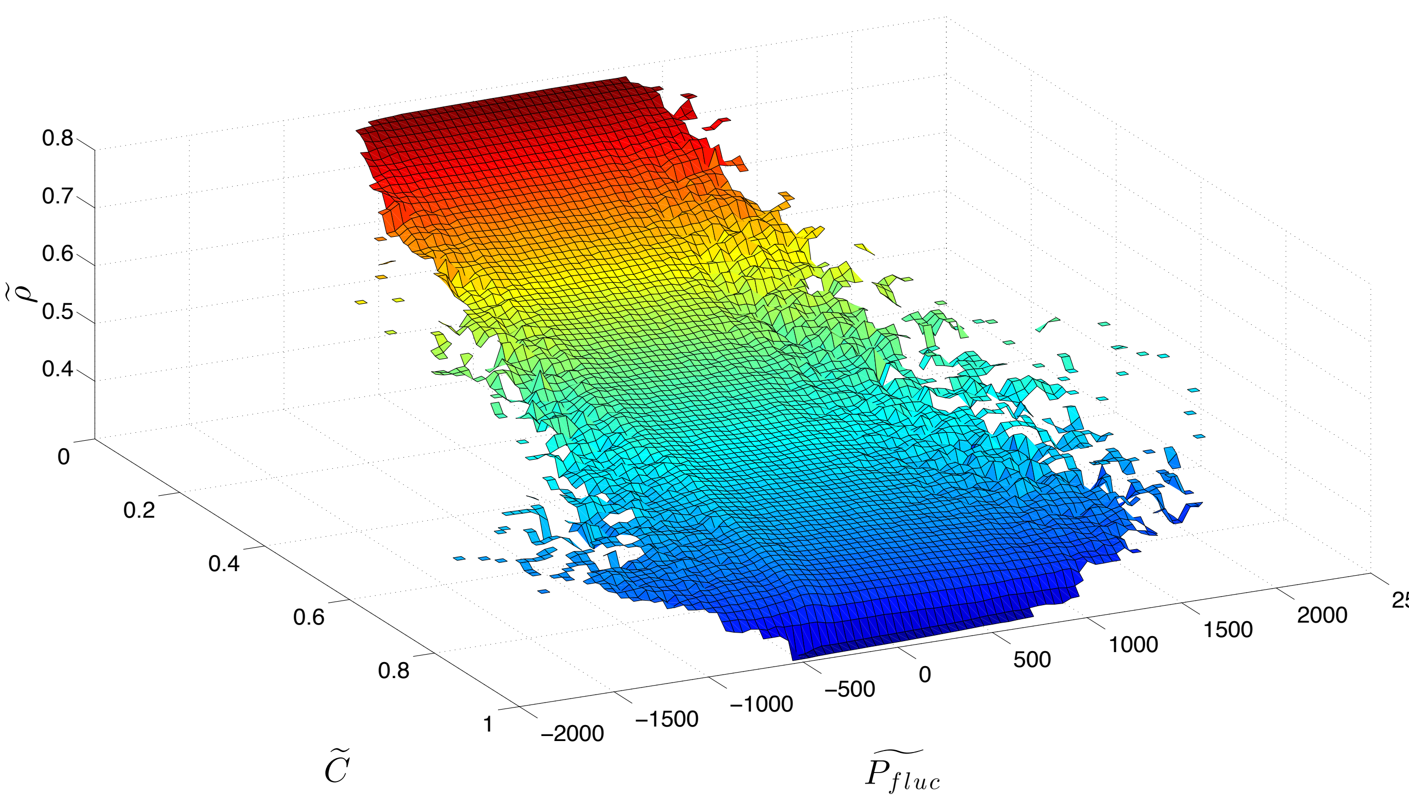
  - Kolmogorov length scale ~ 0.25 mm
  - Laminar flame thickness ~ 0.175 mm



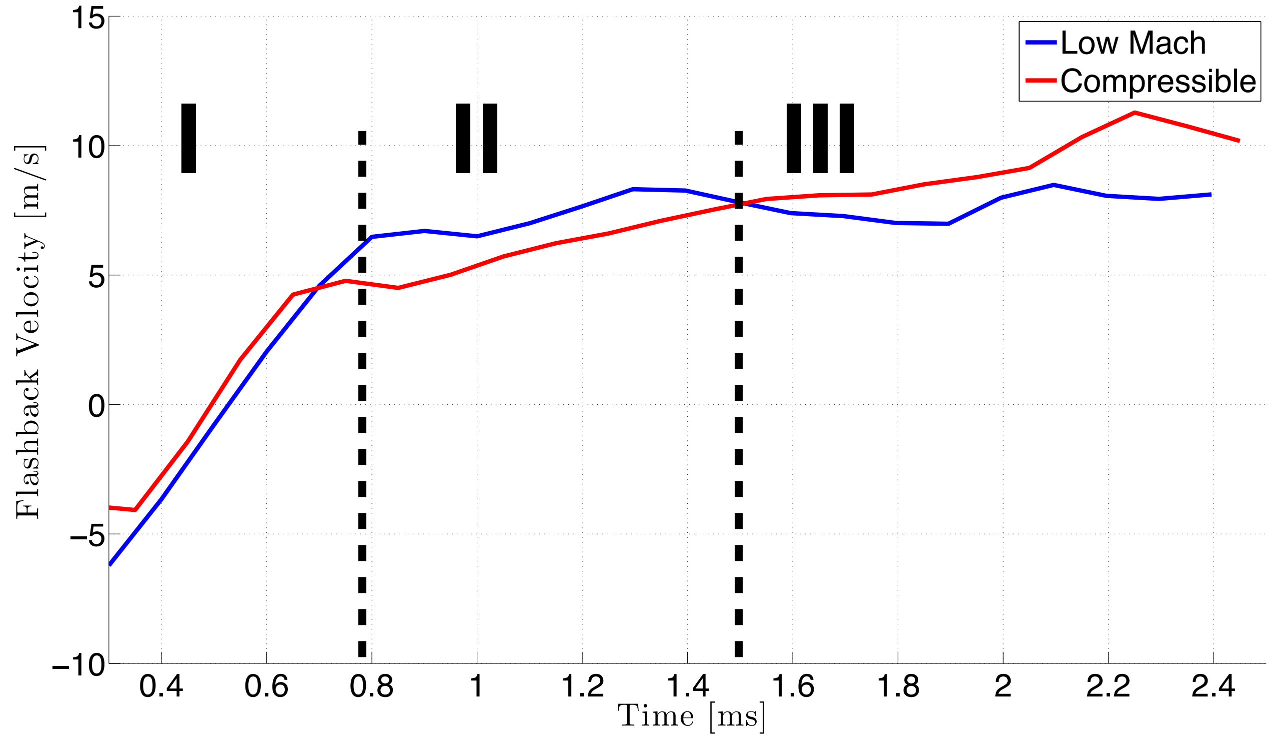
Compressibility regime

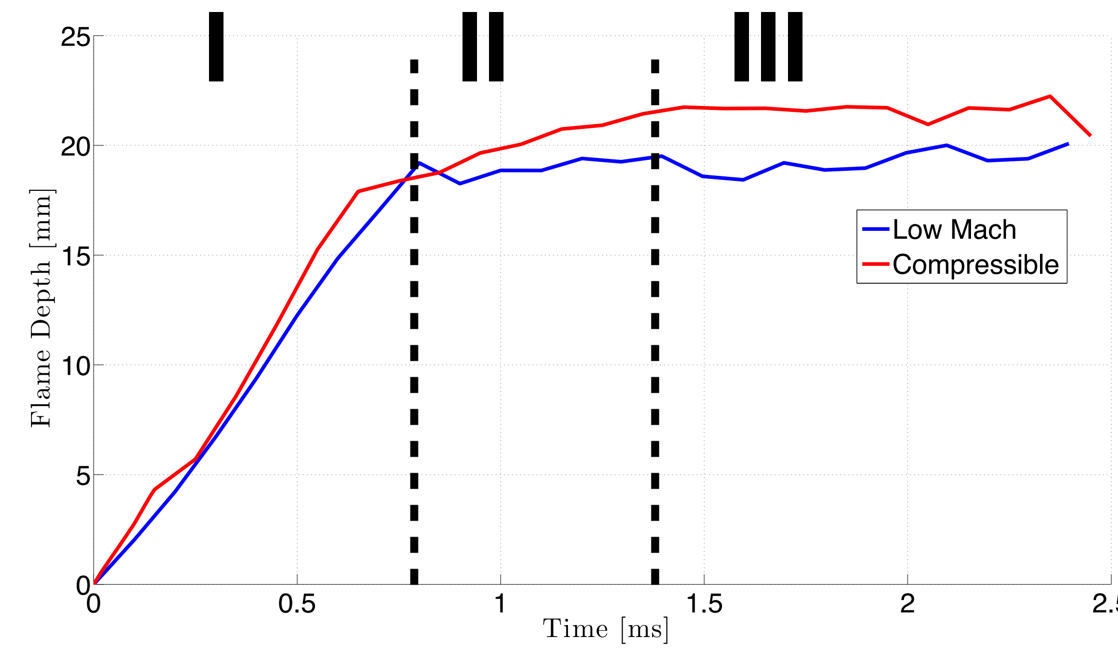
- Ma << 1
  - Far away from compressible regime
- With the compressible solver :
  - $d\rho = \frac{\partial \rho}{\partial C} dC + \frac{\partial \rho}{\partial P} dP$
  - Two competing phenomena affect density : combustion and dynamic pressure
  - The effect of combustion on density overwhelms the effect of local compression

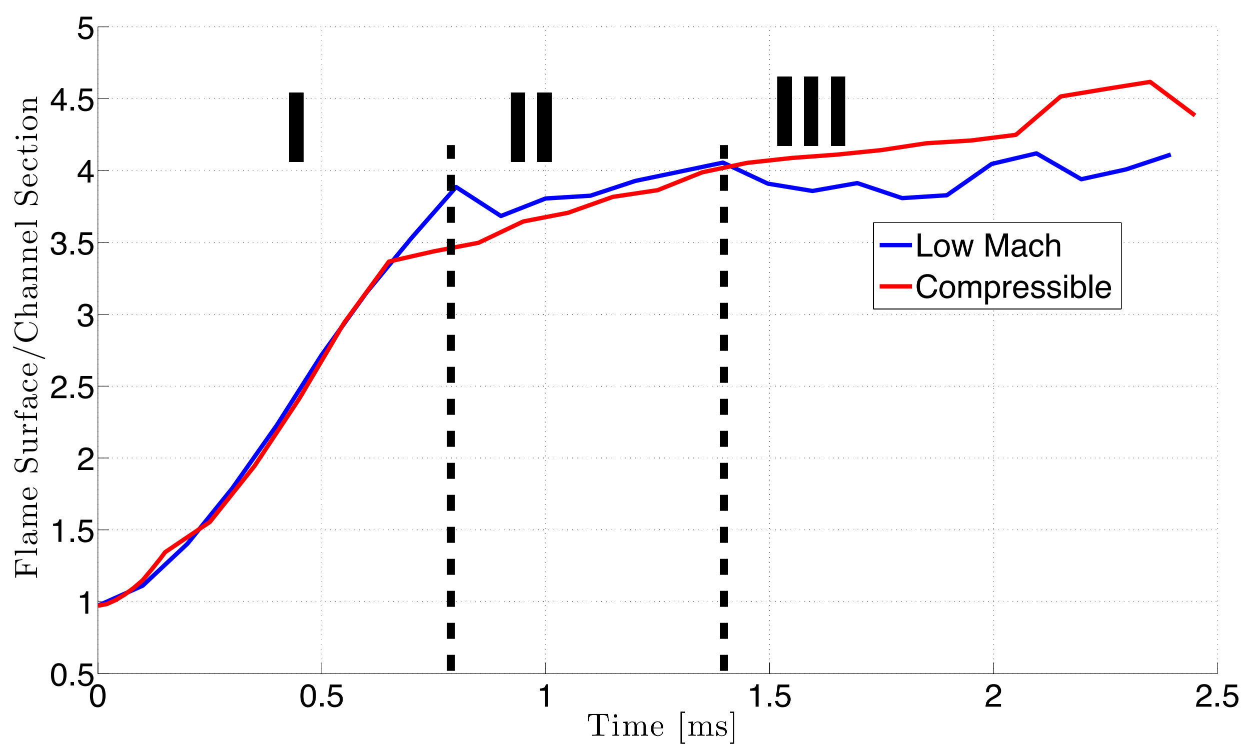




Differences in Flame Characteristics

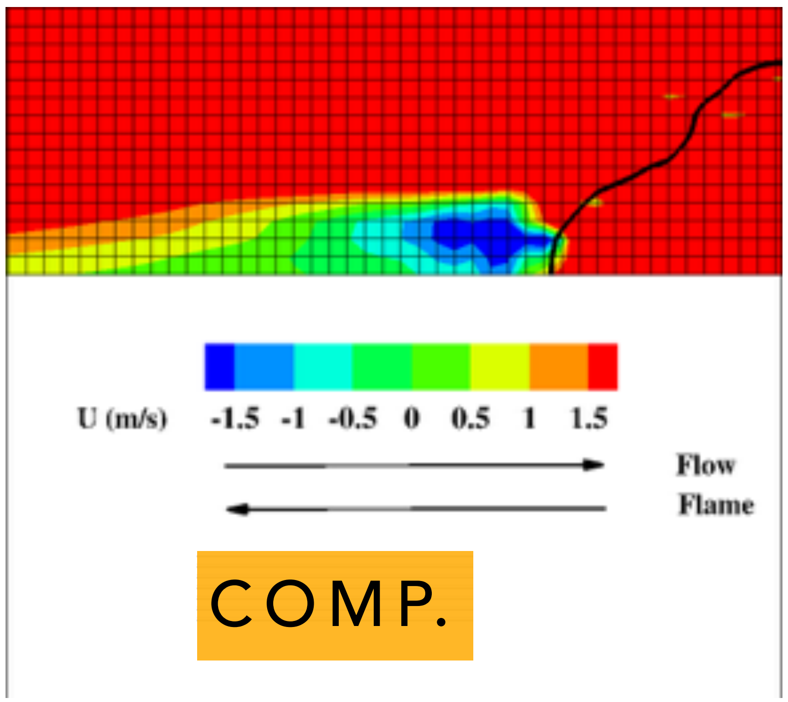


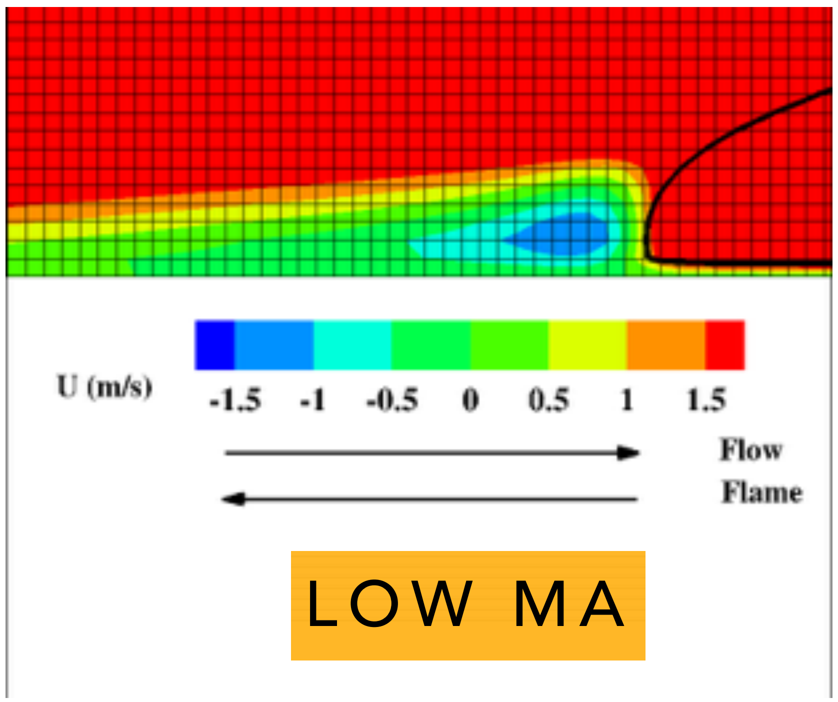


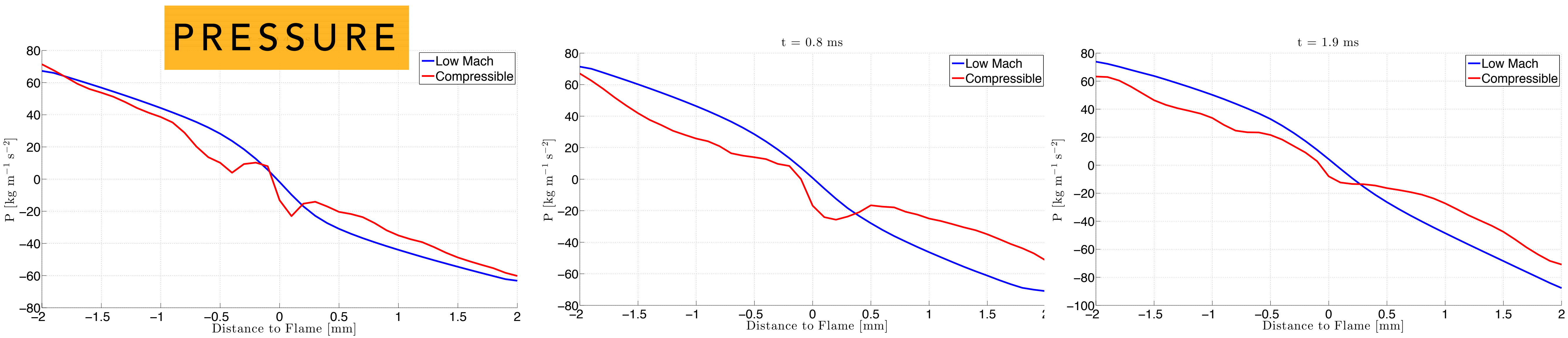


- <u>Phase I :</u> Both solvers are very close during the onset phase.
  The depth stops increasing earlier for the compressible solver leading to a defect in flashback speed.
- <u>Phase II :</u> The depth stabilized for the low Ma number solver but keeps on increasing for the compressible solver. Flashback speed recovers. Wrinkling is underestimated.
- <u>Phase III :</u> The compressible depth is stable but the flashback speed keeps on increasing. Flame wrinkling is increasing.

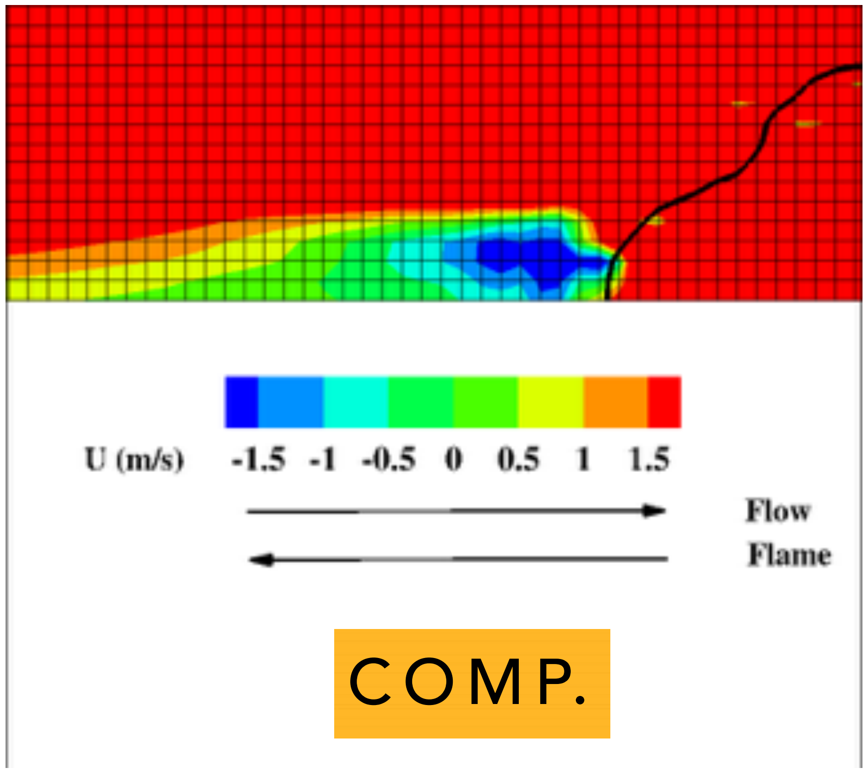
Flame Front Flow Features

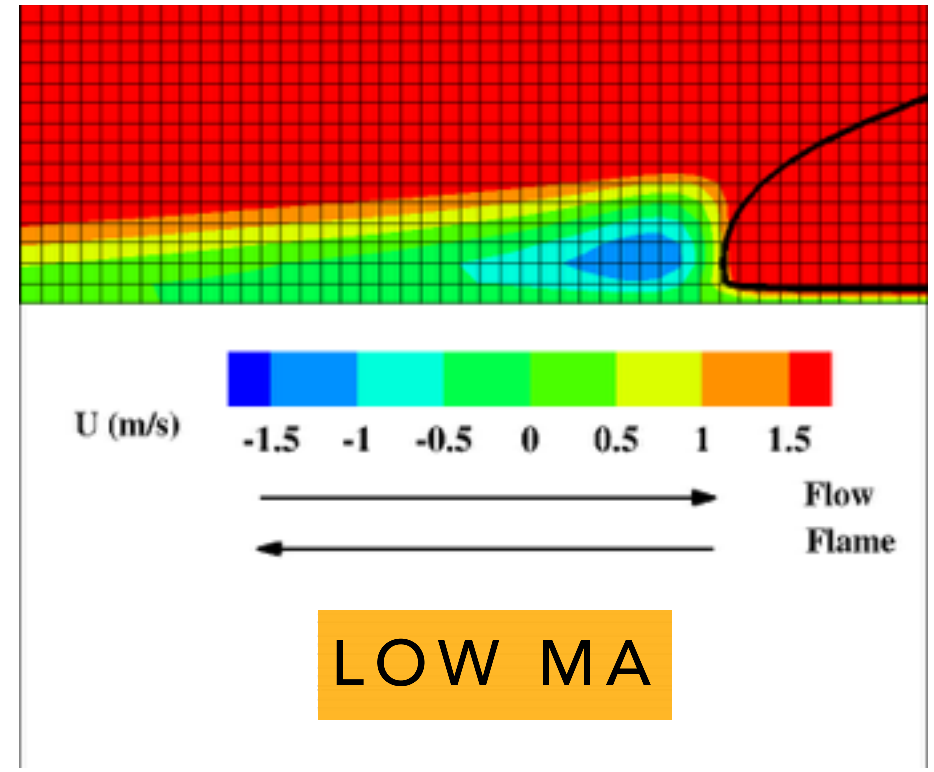


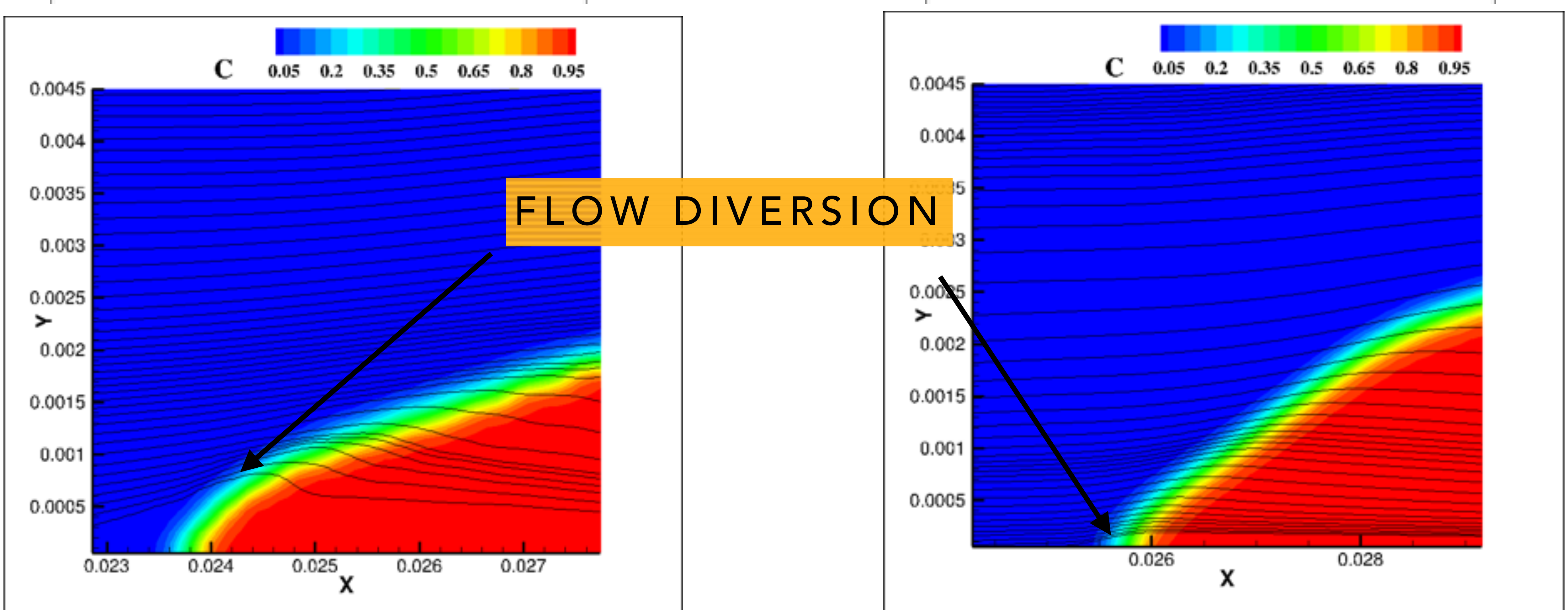




Flame Front Statistics





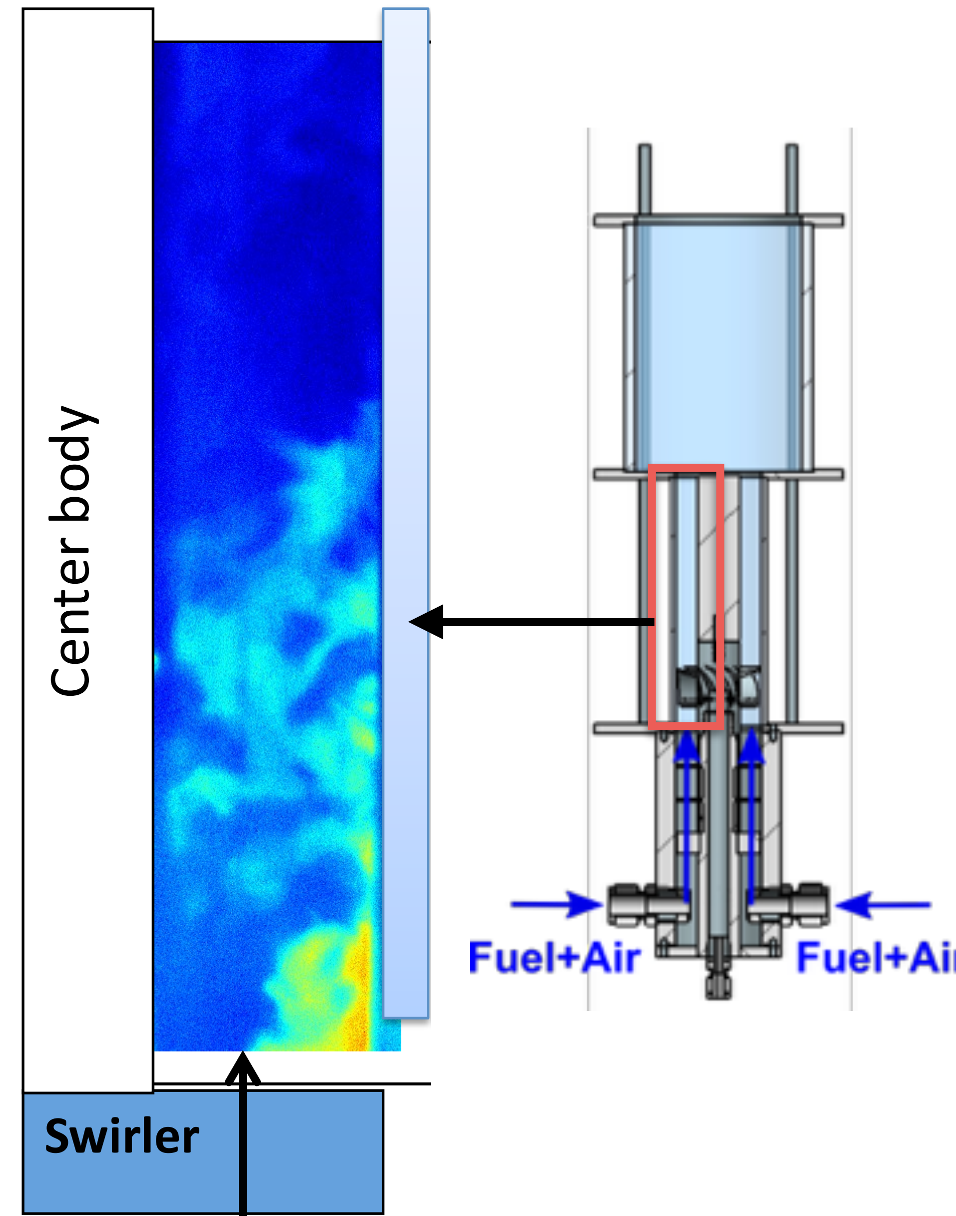


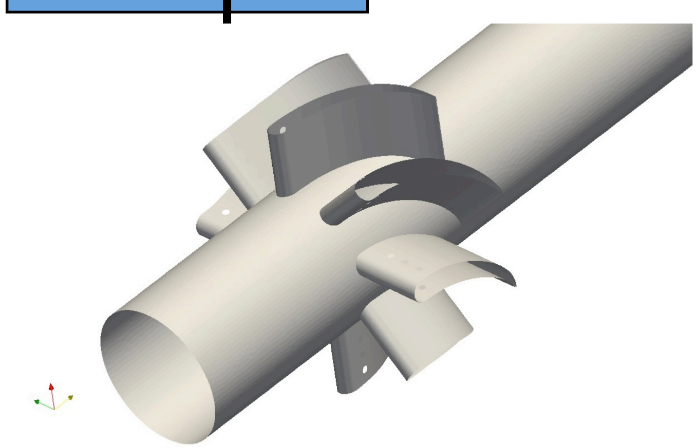
Conclusions #1

- **Low Ma version predicts global characteristics**
  - ➡ Differs significantly from compressible formulation
  - ➡ Introduces uncertainty in the results
- **Current plan**
  - ➡ Test low-Ma and compressible solvers for a variety of flashback conditions; estimate differences
  - ➡ Ensure that low-Ma solver is reliable for the range of conditions tested
    - Else, develop compressibility-enhanced versions
      - One approach is to introduce acoustics-based techniques

Effect of Stratification

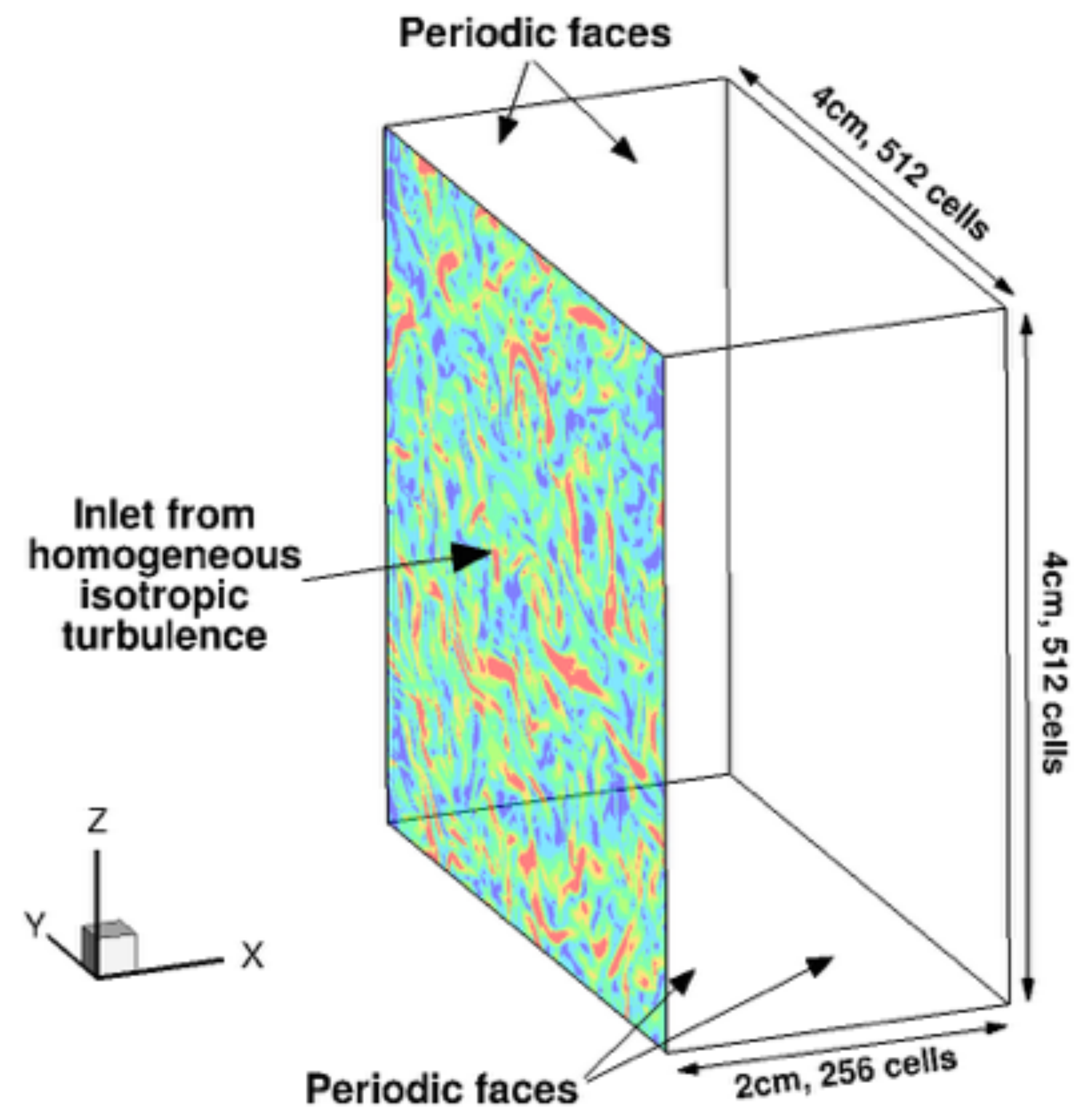
- **Strategy for flashback control**
  - ➡ Introduce stratification
  - ➡ Leaner mixtures injected near walls
- **How does stratification affect flashback**
  - ➡ Mixture no longer with constant equivalence ratio
  - ➡ Premixed combustion models cannot be used
- **For stratification in gas turbines**
  - ➡ Is the flame structure altered?





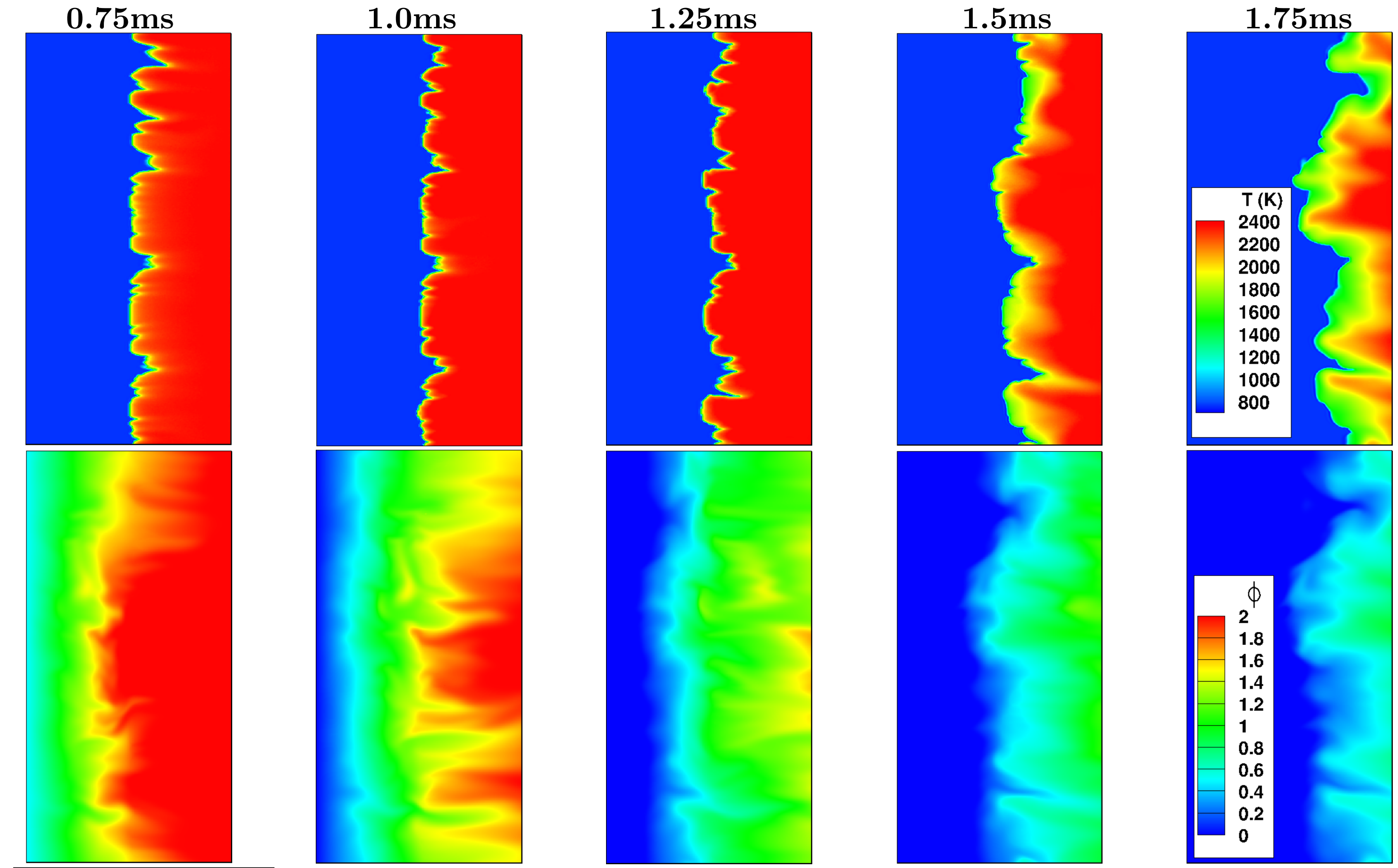
DNS of Flame in a Box

- **DNS of homogeneous isotropic turbulence with uniform mean flow**
  - ➡ Detailed chemical kinetics
- **Two cases**
  - ➡ Large scale stratification
    - Inflow equivalence ratio varied from 2 to 0 over 3/4 residence time
  - ➡ Small scale stratification
    - Equivalence ratio variations introduced as small-scale structures

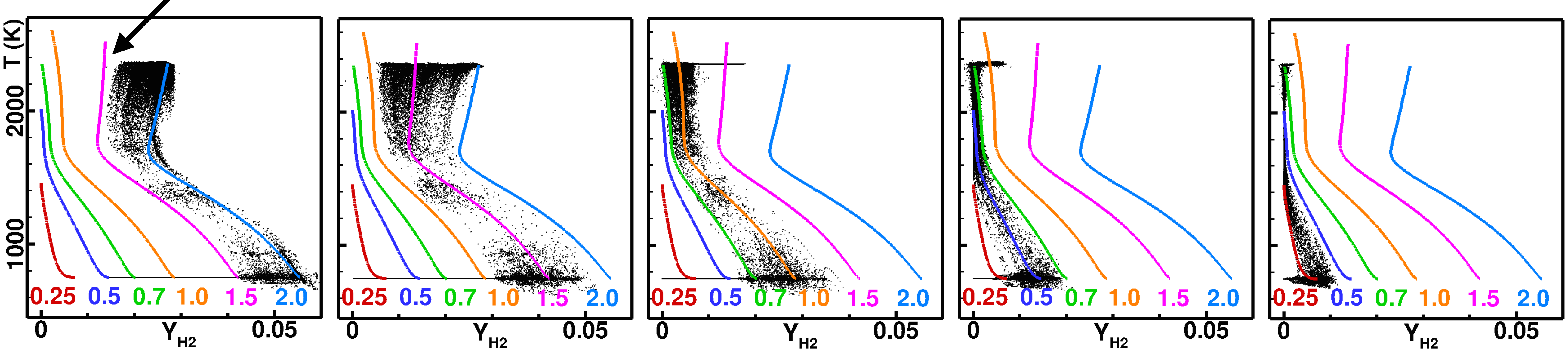


Large-scale Stratification

- Flame structure a sequence of flamelets
- Equivalence ratio is variation not sufficient to affect flame front

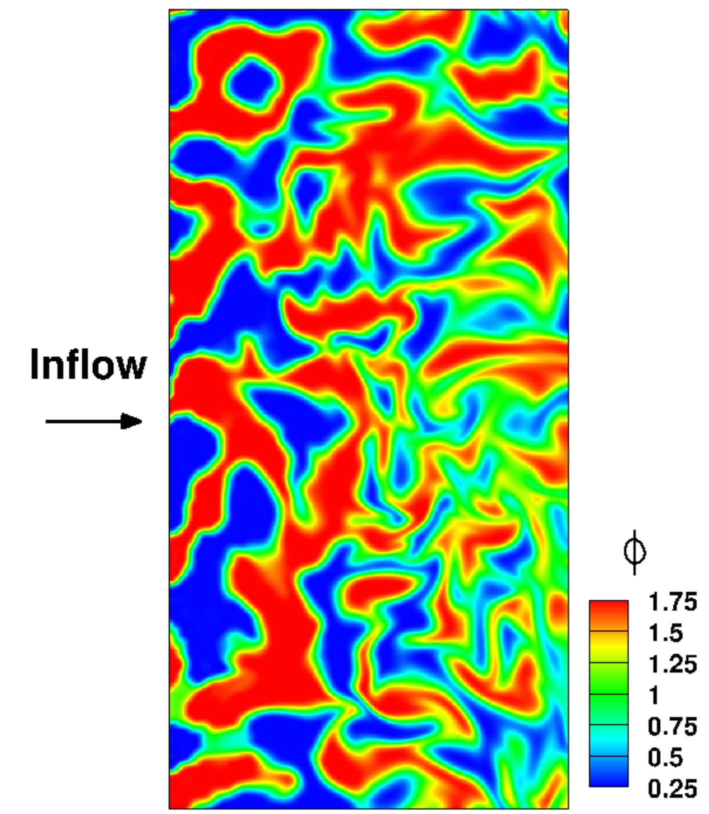


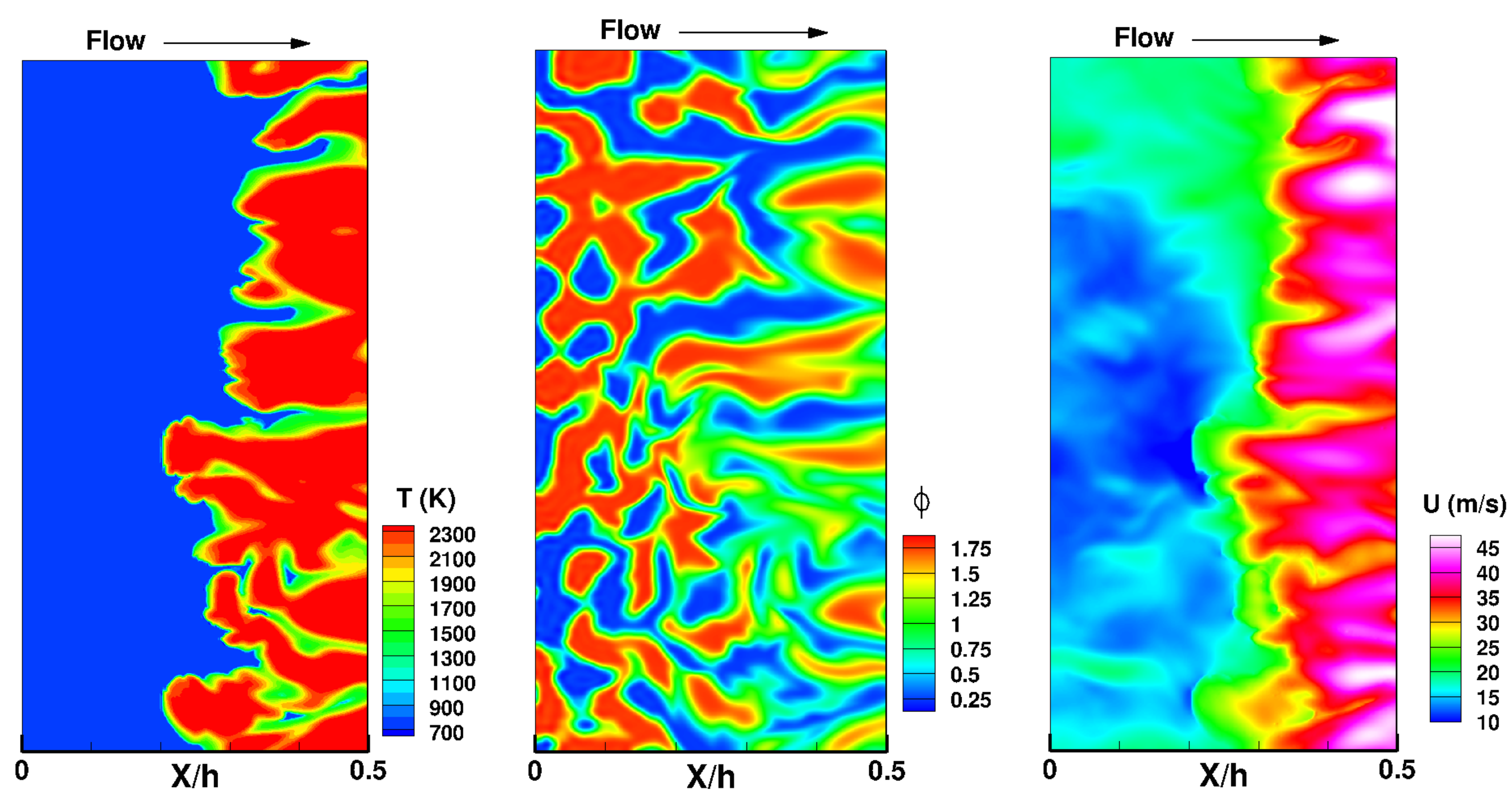
FLAMELET SOLUTIONS

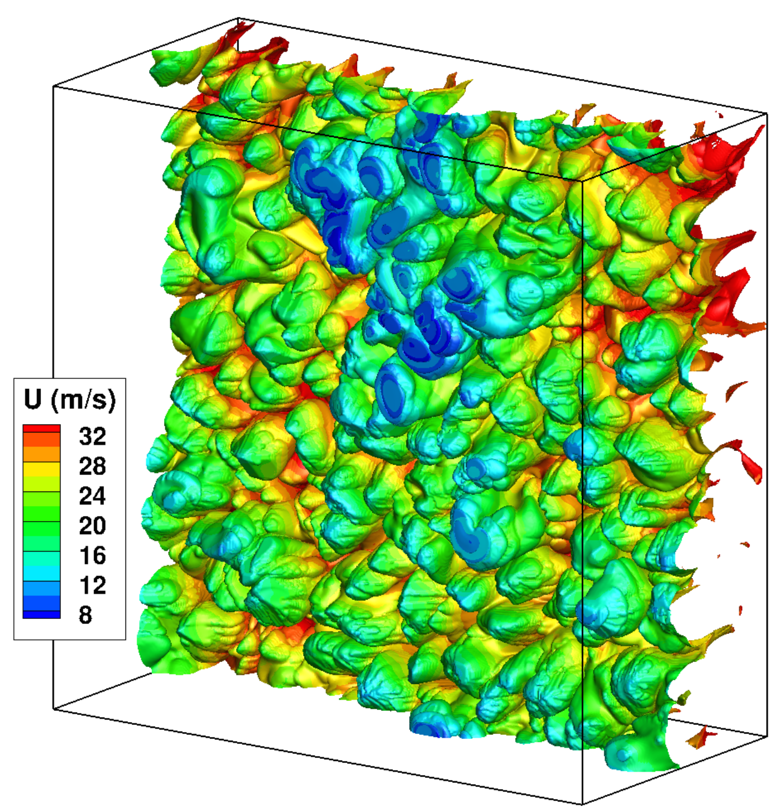


Small-scale Stratification

- Scalars generated using model spectrum
- Peak energy at 1/12 domain height
- Statistically stationary case





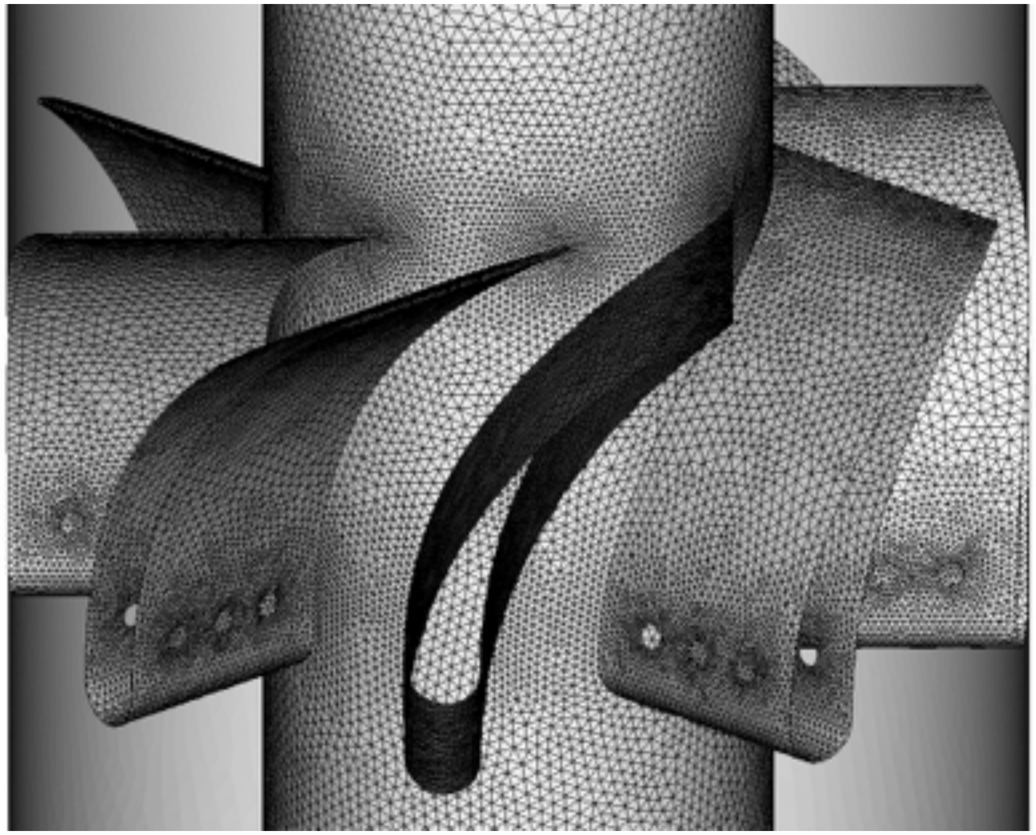


Conclusions #2

- **Small-scale stratified flame significantly different**
  - ➡ Post-flame velocities are lower
  - ➡ Less flame wrinkling
  - ➡ Distributed heat release
- **Current plan**
  - ➡ Complete DNS studies
  - ➡ Establish base line models for stratified mixtures
    - Choice between PDF-based approaches or flame-surface based approaches

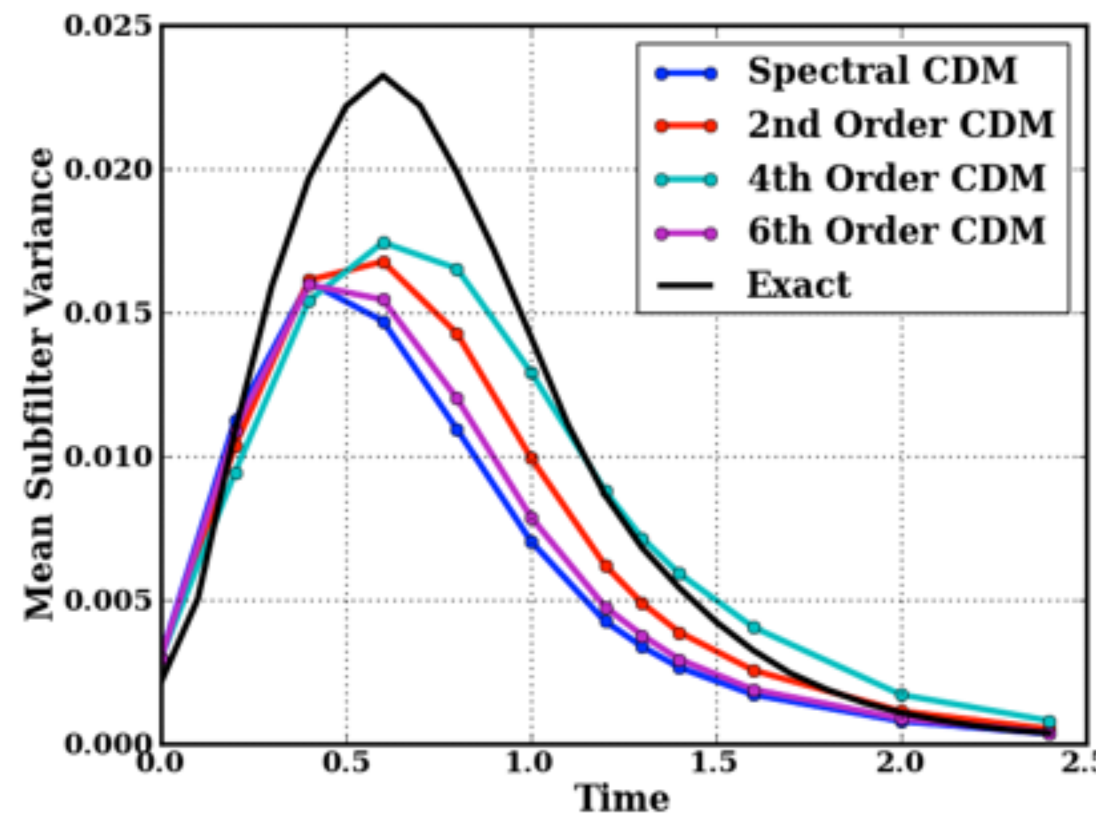
Numerical Modeling of Flames

- **LES is the accepted tool for modeling turbulent flames**
- **LES has unique challenges**
  - ➡ Strong interference of numerical method on solution
  - ➡ Grid convergence is all-but-impossible
- **How to mitigate numerical errors?**
- **Current model development procedure**
  - ➡ Relies exclusively on structured grids
    - Toy problems of very little relevance to industry
- **Is there an effect of unsteadiness on model formulations?**



Numerical Errors in LES

- **LES resolves a range of turbulent length scales**
  - ➡ A spectrum of wavenumbers
- **Numerical methods used to discretize partial differential equations**
  - ➡ Assume smooth underlying flow field
    - Not correct for turbulent flow
    - Introduces errors
  - ➡ Numerical errors scale with wavenumber
    - Highest errors at filter scale
    - Contaminates numerical solution
    - Can lead to counterintuitive behavior



Flame Surface Models

- **For premixed combustion at moderate Reynolds numbers**
  - ➡ Flame surface models are reasonable
  - ➡ The motion of flame surface is treated using a single field variable
    - G (level-set) variable or progress variable
- **Level set approach**
  - ➡ Numerically better suited for predicting flame surface
    - However, encounters flame volume loss
  - ➡ Difficult to transition to stratified combustion models
- **Approach used here: Progress variable description**

Progress Variable Approach and Flashback

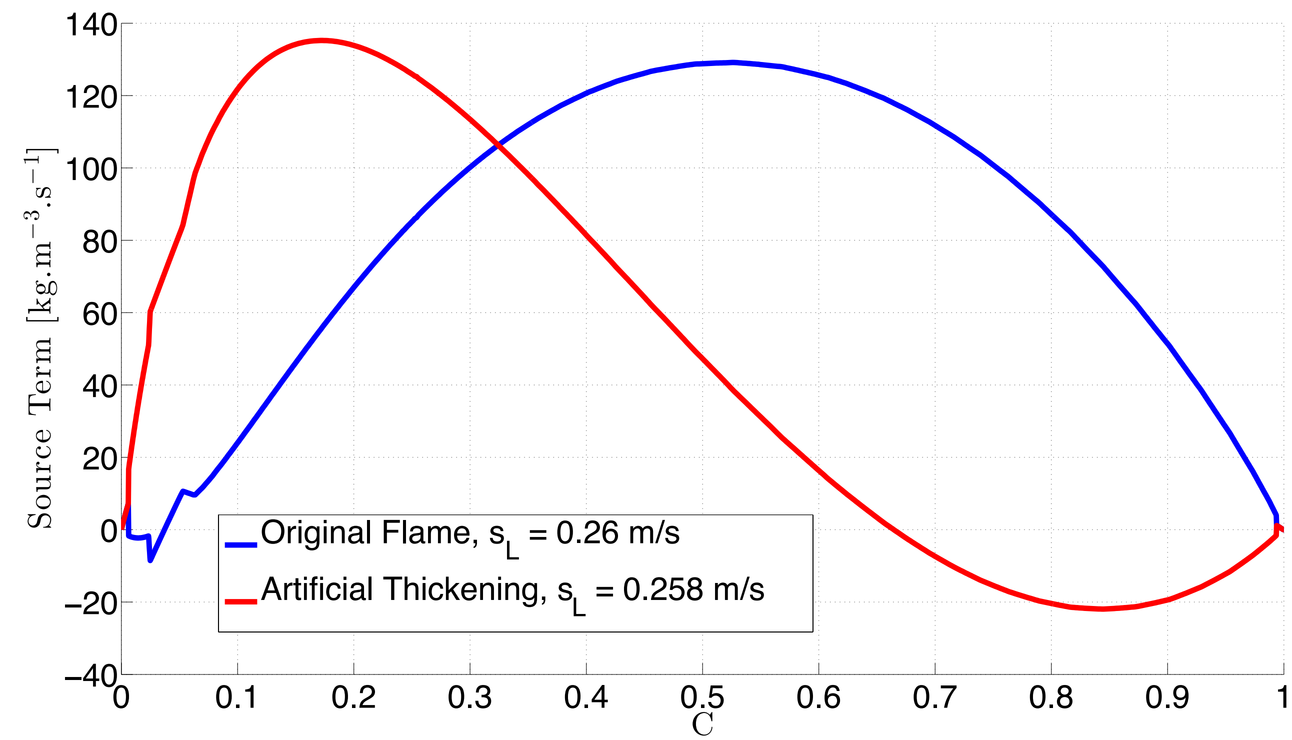
- **Transport equation for C**

$$\frac{\partial \rho C}{\partial t} + \nabla \cdot (\rho U C) = \nabla \cdot (D(C)\nabla C) + \dot{\omega}(C)$$

  - ➡ Filtered; Leads to unclosed terms; Need modeling

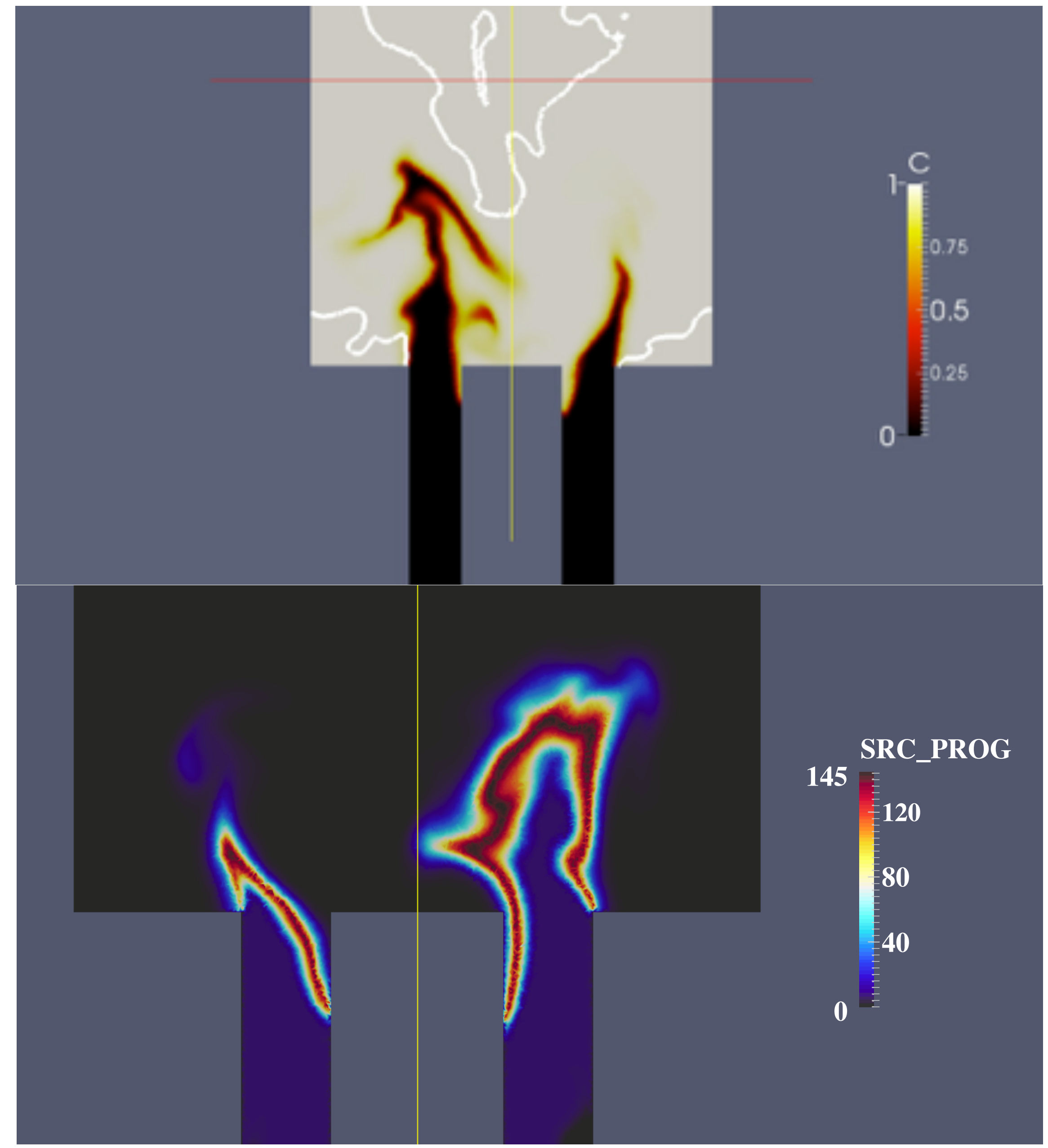
- **Models for chemical source term**
  - ➡ Require underlying flame structure

- **LES problem**
  - ➡ Imposed flame structure is not maintained as simulation proceeds
  - ➡ Not a big issue for steady-state problems
  - ➡ Unsteady flashback accumulates these errors over time



Flame Thickness

- **Model closures use two different terms**
  - ➡ Imposed flame thickness (L) and source term
  - ➡ Product is proportional to consumption speed
- **Counter-intuitive LES behavior**
  - ➡ Flame thickness is reduced with time
    - Leads to reduced burning rate
    - Arrests flashback



Structure-Preserving Reaction Model

- **Treat progress variable discretely (in space and time)**

$$C(t+\Delta t) = C(t) + f(C,u)$$

- **Introduce time-dependent translation**

$$F : C(x,t) \to \widetilde{C(x,t)} = C(x - (\frac{\rho_0 s_L t}{\rho(C)} - \frac{1}{\rho(C)}\int_0^t \rho u(t')dt'), t)$$

- **We require the distribution of $\widetilde{C(x,t)}$ to be independent of time**

- **Introduces numerical flame structure**

$$f(x,t) = (\frac{\rho_0 s_L}{\rho(x,t)} - \frac{1}{dt}\int_t^{t+dt} u(t')dt')\frac{\partial \widetilde{C}}{\partial x}$$

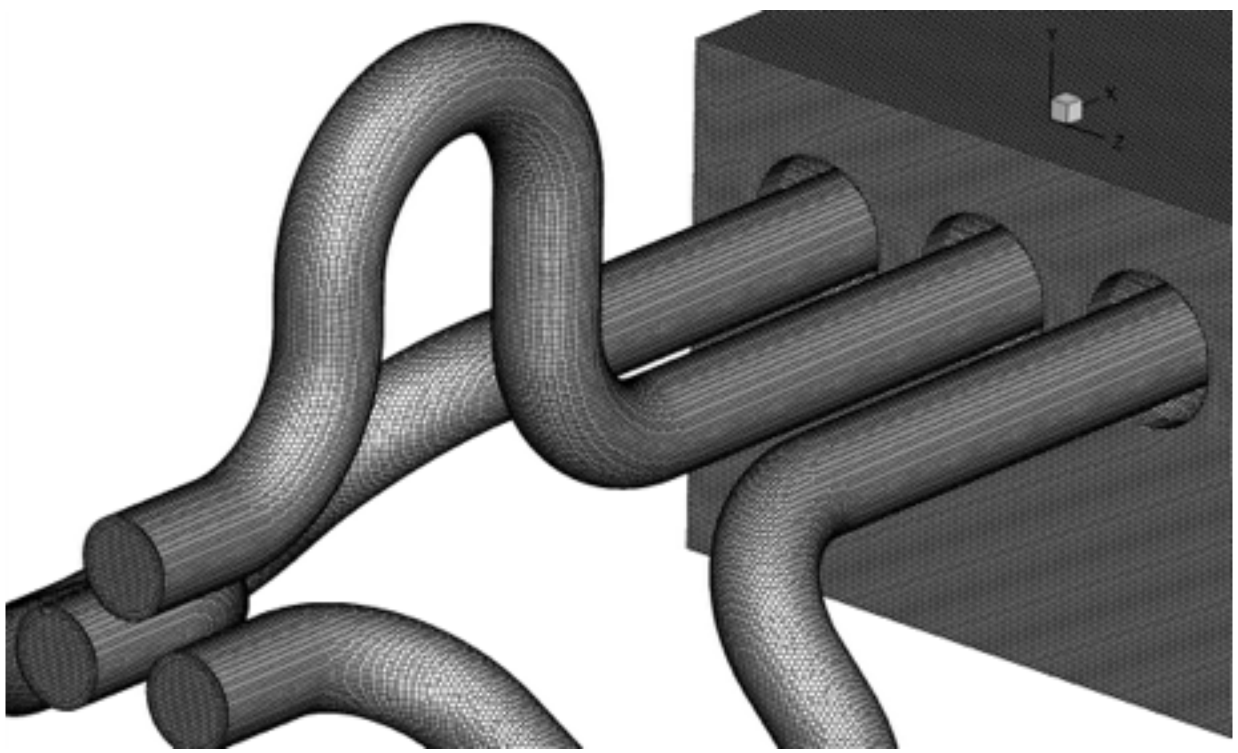
- **Guarantees constant local flame speed; Enables consistent flame thickening**

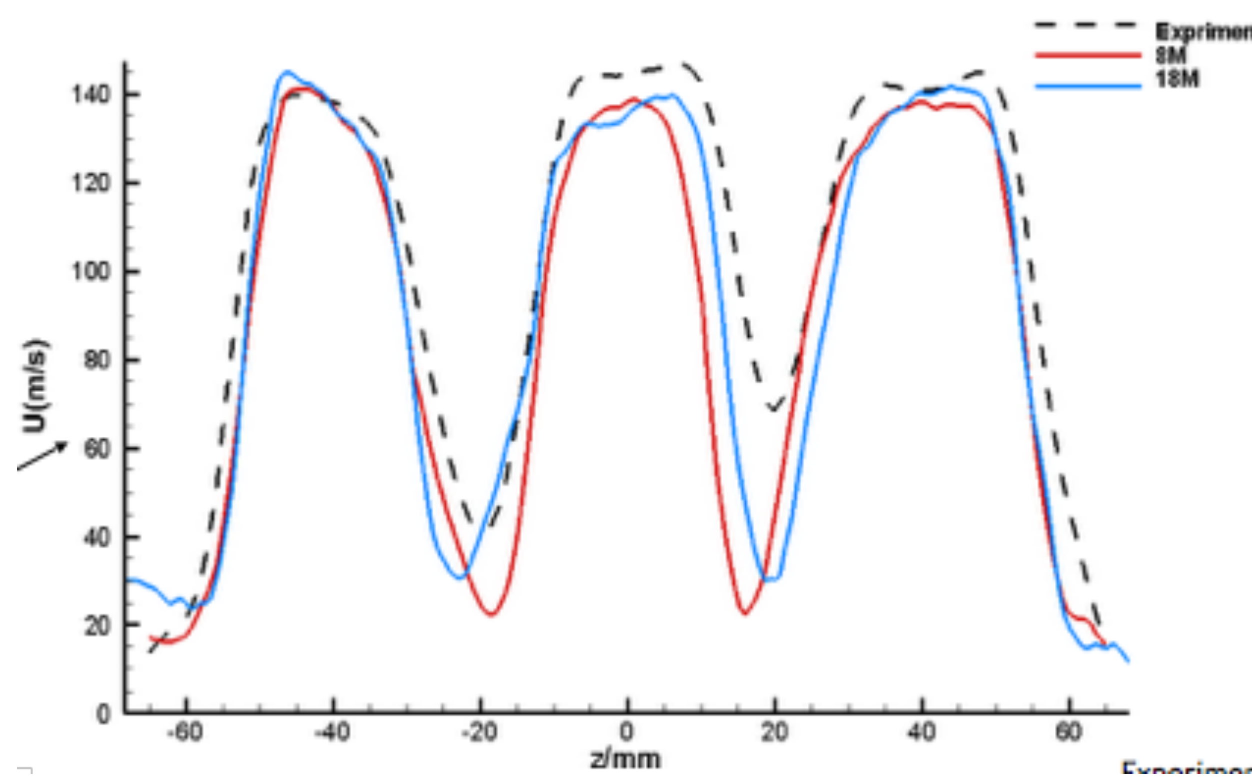
Open Source Gas Turbine Software Platform

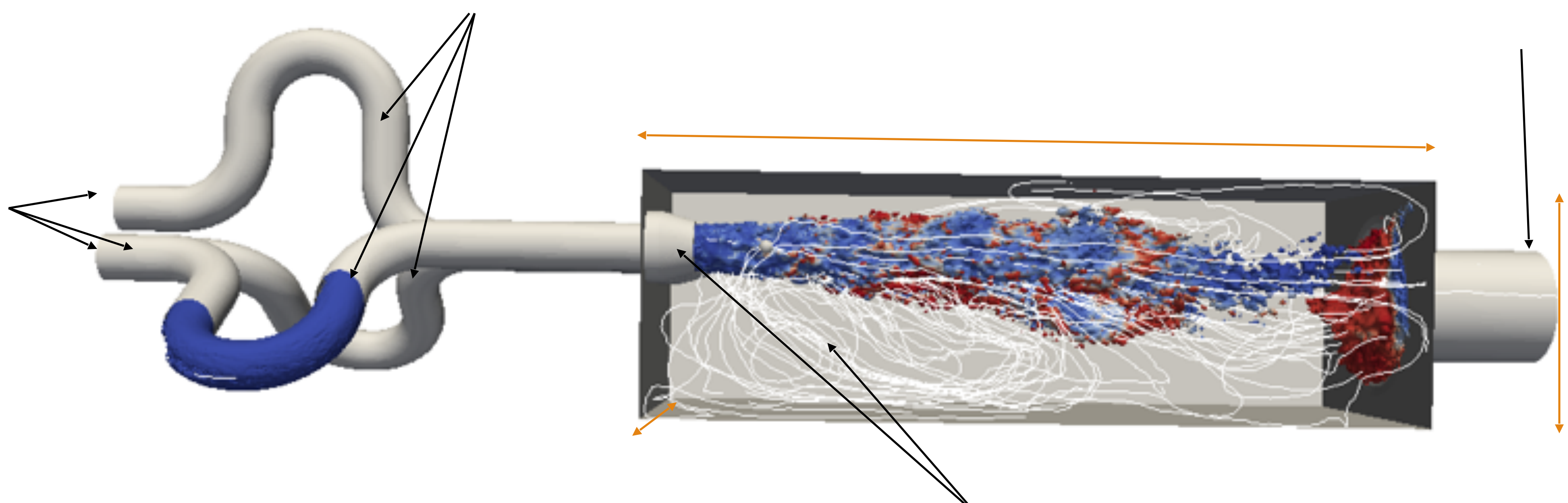
- **Integral part of the flashback model project**
- **Enable rapid dissemination of results**
- **Prior collaboration with Siemens**
- **Currently working with Oregon State, Iowa State, KAUST, UT Austin, and Princeton on enhancing capabilities**
- **Progress in last year**
  - ➡ All models implemented in OpenFOAM
  - ➡ Minimal kinetic energy dissipation enforced

Siemens DLR 3-jet Combustor

- **Lean combustion with heat loss**







Next Steps

- **Develop structure-preserving reaction model**
  - ➡ Implement and validate using UT swirler data and legacy data (Darmstadt)
- **Develop stratified combustion model with heat loss**
  - ➡ Conduct DNS to evaluate flame structure
  - ➡ Identify model formulations
- **Fuel effects at high pressure**
  - ➡ Identify the role of differential diffusion, and fuel composition on boundary-layer/flame interaction
    - Experiments and DNS data