Experiments and LES Modeling of Flashback in a Model Swirl Combustor

Noel Clemens
The University of Texas at Austin
Venkat Raman
University of Michigan

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WHAT STARTS HERE CHANGES THE WORLD

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Objectives

Joint Experimental/Computational program

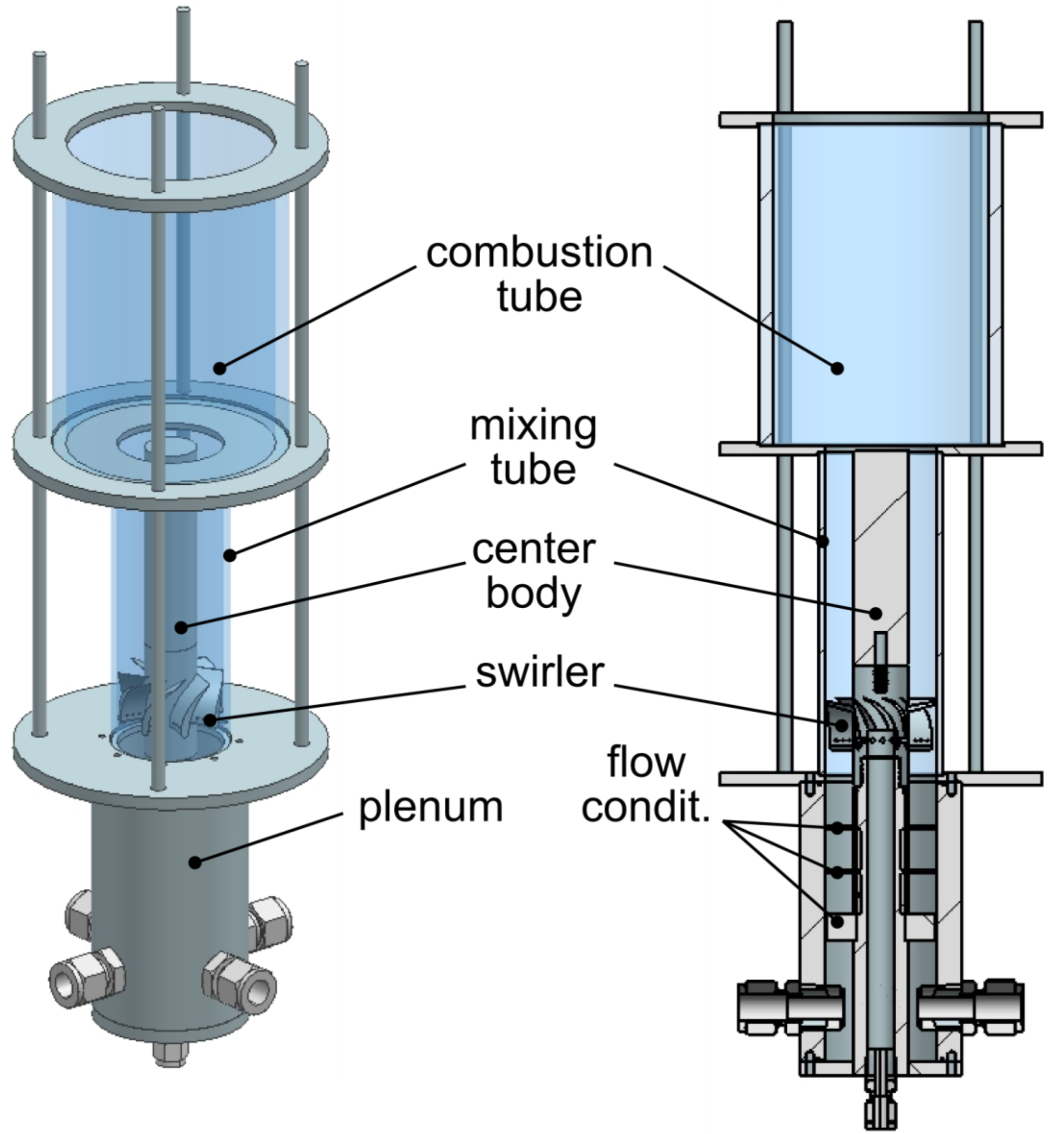
- Investgate boundary layer flashback in swirl combustors with hydrogen enriched fuels
- Develop improved LES models for this challenging target problem
- Use OpenFOAM platform to facilitate transfer to industry
- Conduct experiments in a newly-developed swirl combustor under varying pressure conditions
- Make high-fidelity time-resolved measurements for physics and validation

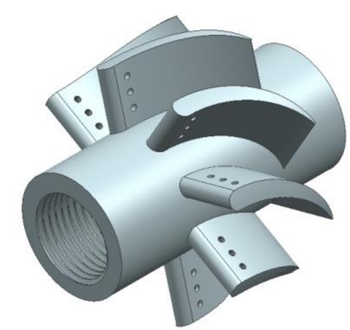
Current Presentation

- New Experimental Results
  - Solid particle seeding to enable velocity measurements in unburnt and burnt gases
  - Tomographic PIV and flame front measurements
  - Measurements of flashback at pressures up to 5 atm
- New LES Results
  - New models have been developed to improve prediction of turbulence in non-reacting flow and in presence of flame
    - Extensive validation with literature and UT data

Model Swirl Combustor

Model swirl combustor

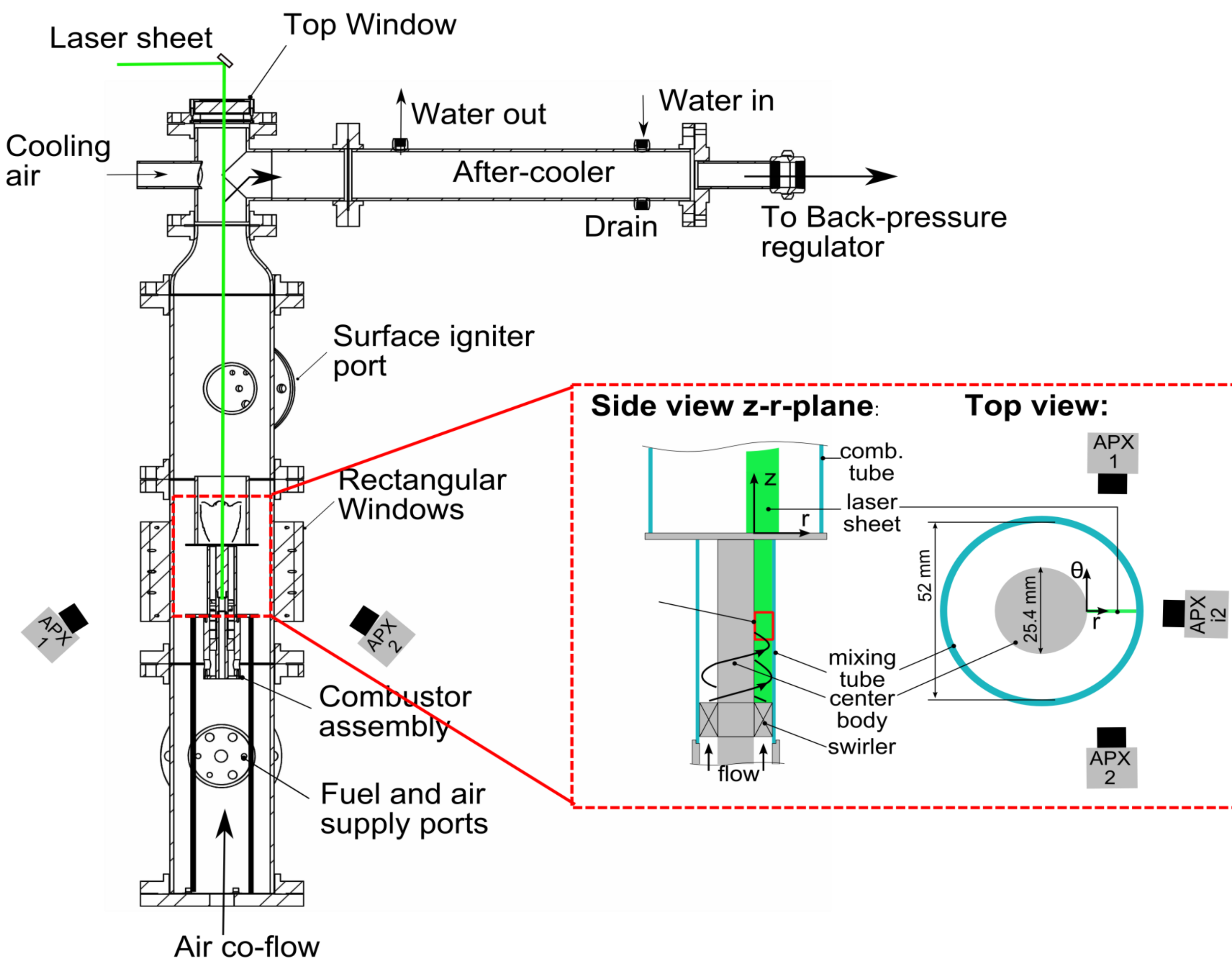




High-Pressure Combustion Facility

- Designed to operate at up to 10 bar
- 8” internal diameter
- Stainless steel construction
- Allows mounting of various burners
  - Flashback
  - Stratified flames
- Optical access through sides and top
- To date we have operated it only to 5 bar

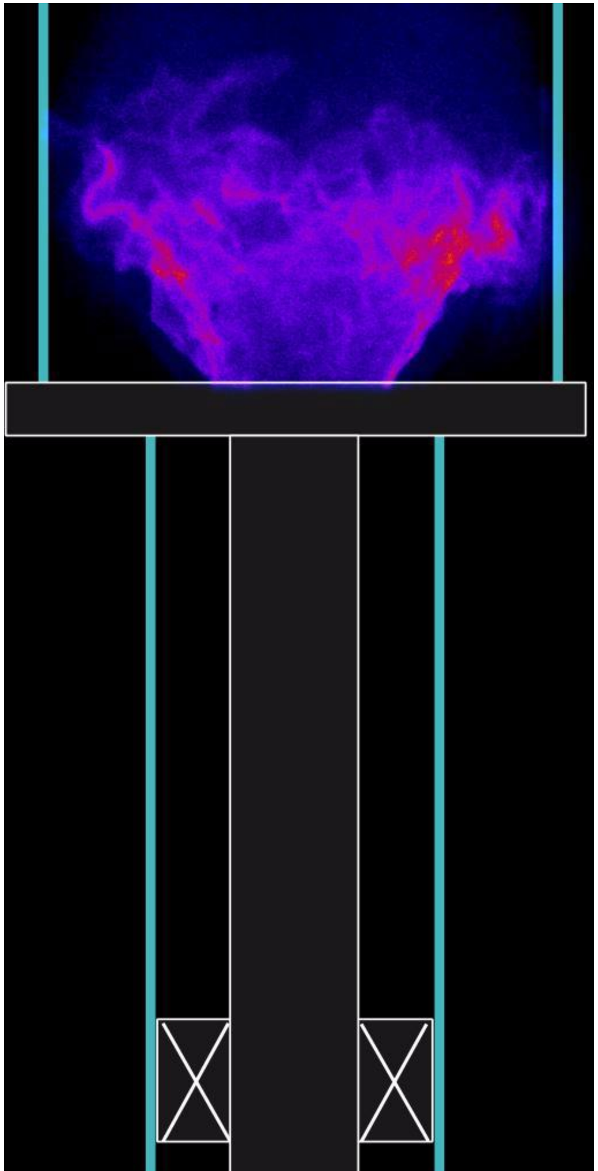
High-Pressure Combustion Facility



Measurements at 1 atm

CH_4-air flames

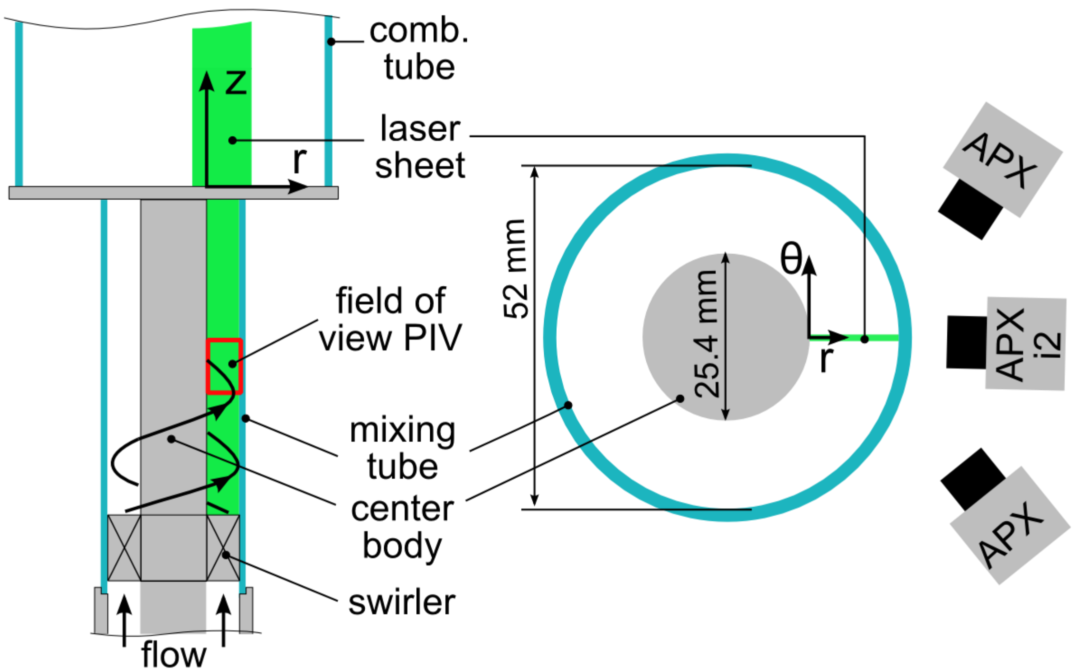
Flashback: CH_4-air at Re_h = 2000



- High-speed chemiluminescence imaging (2 kHz)
- Flashback along center body in swirling motion
- Flame stabilizes on trailing edges of swirler vanes

High-speed particle image velocimetry

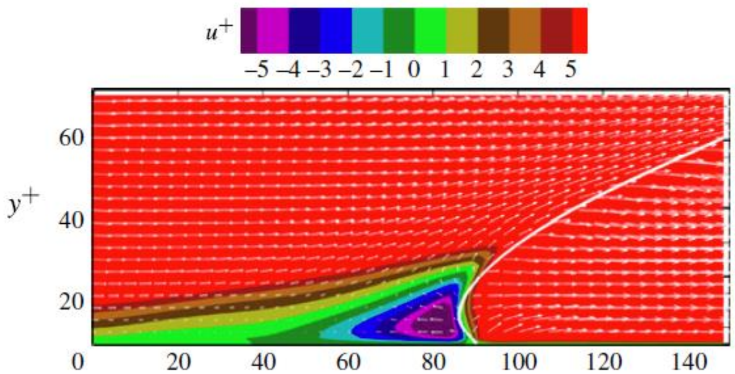
Simultaneous 3-component (stereo-)PIV and flame luminescence imaging



- 4 kHz framing rate
- Spatial resolution: one vector every 0.4mm
- Flame front detection based on vaporized seeding particles

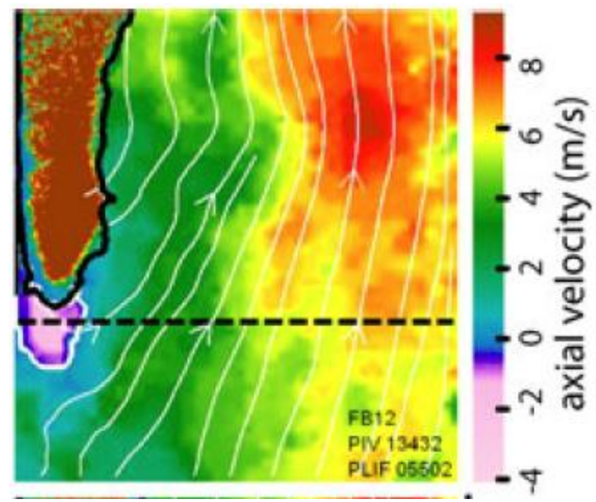
BL flashback (last year's results)

Channel flow



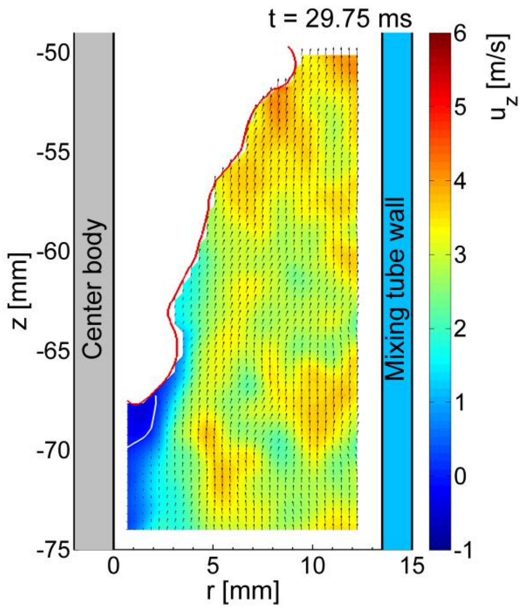
Gruber et al. *JFM,* 2012

Swirling flow



Heeger et al., *EXIF,* 2010

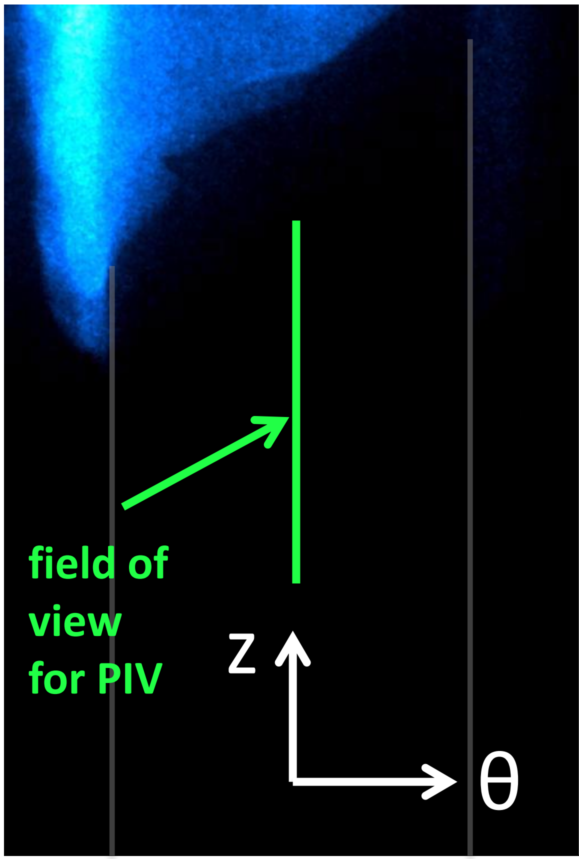
Current work



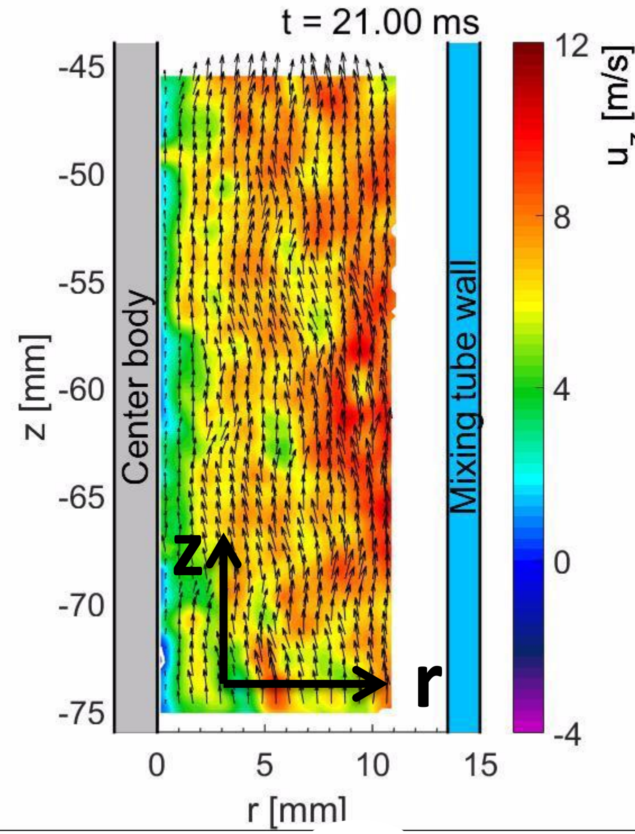
- Is this flow reversed or separated?
  - Need 3D measurements

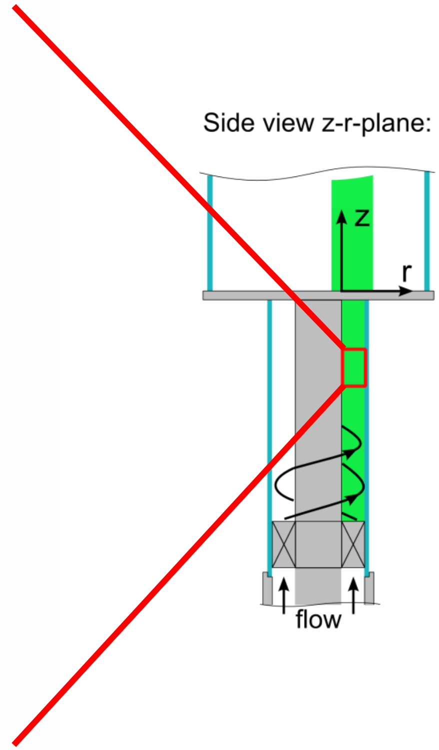
Planar PIV in unburnt *and* burnt gas

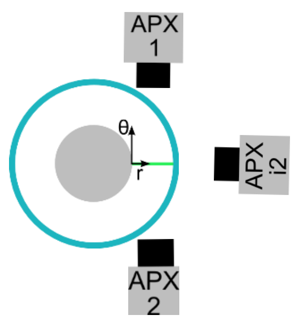
flame luminescence

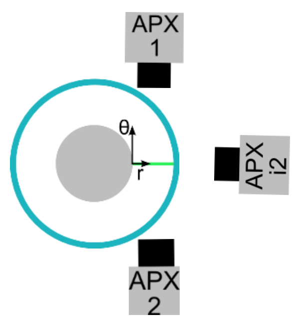


axial velocity



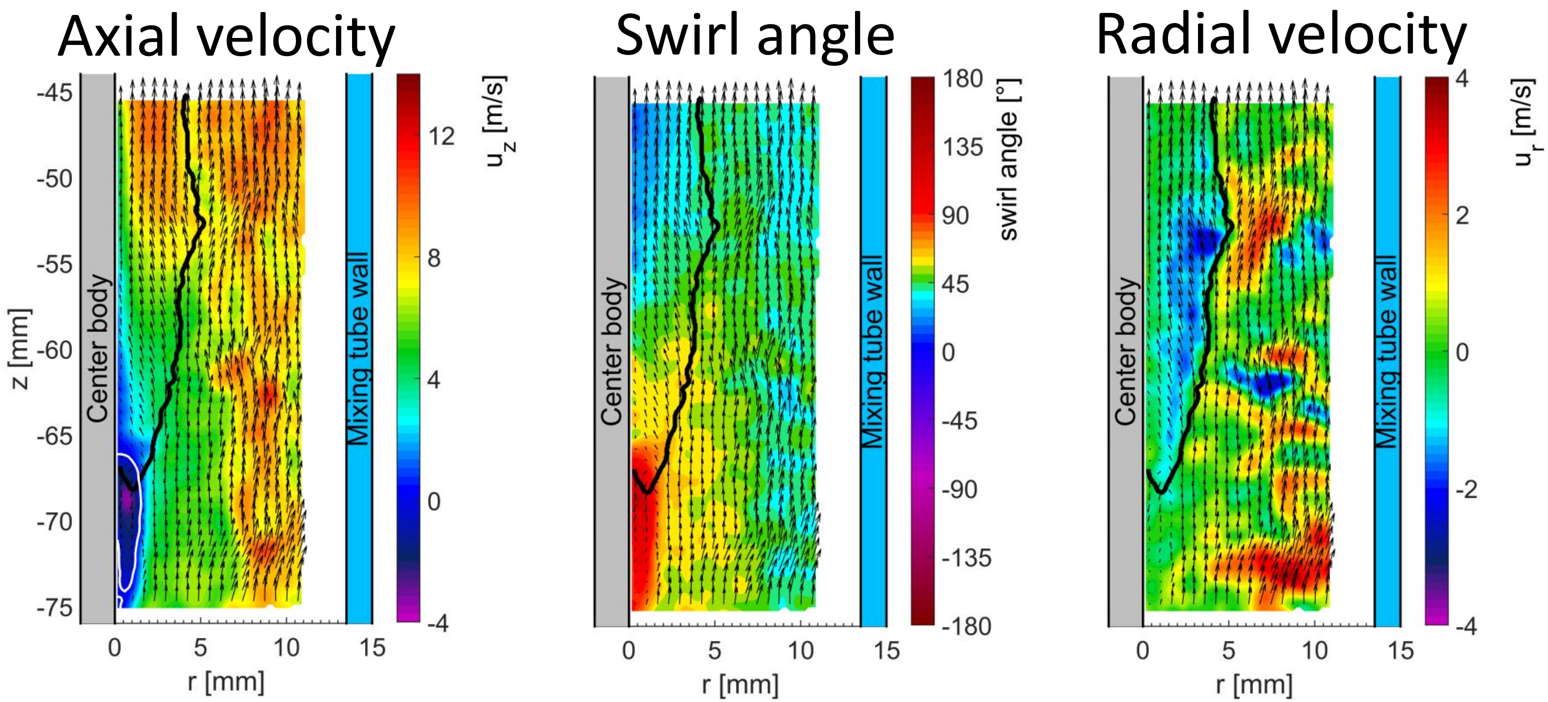






Planar PIV in unburnt *and* burnt gas

Improved data for validation



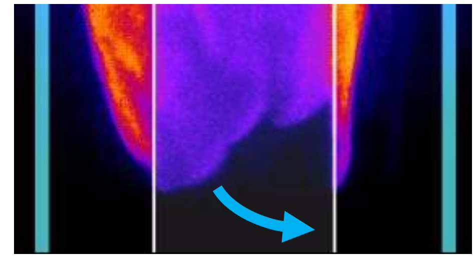
- Moderate acceleration in the axial direction in burnt gas farther downstream of flame tip
- Swirl decreases in burnt gas – realignment of streamlines

Measurements at 1 atm

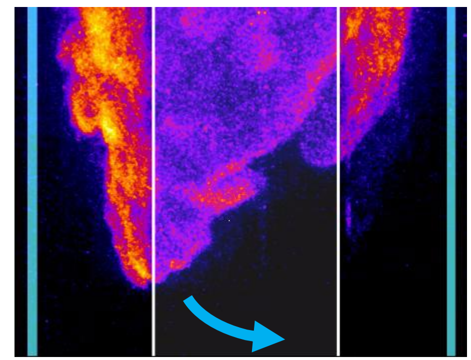
H_2-enriched flames

Flashback Modes (new interpretation)

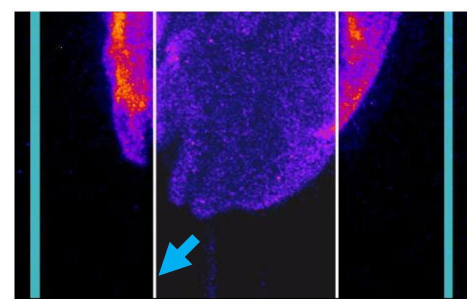
- “Swirl-flow flashback”
  - Flame tongues swirl around centerbody as they propagate upstream
  - Found in both CH_4 and H_2 cases
- “Channel-flow flashback”
  - Flame cusps convex towards reactants propagate upstream in streamline direction
  - Occurs on windward side of flame tongue
  - Found in H2 and CH4 flames
  - Mechanism seems to be similar to that in non-swirling channel flow flashback



CH_4



H_2/CH_4 (90% H_2 by vol.)



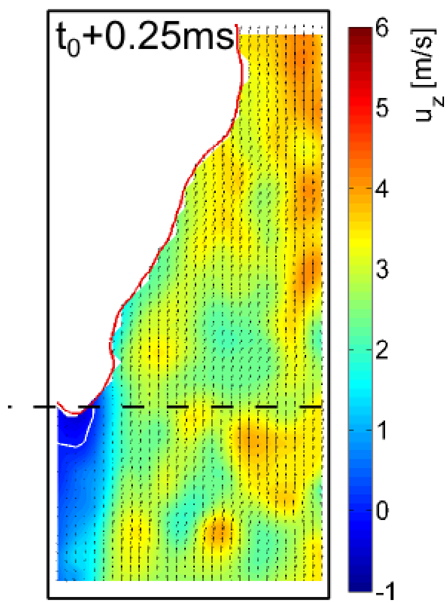
H_2/CH_4 (90% H_2 by vol.)

Flame Spread – Effect of Hydrogen

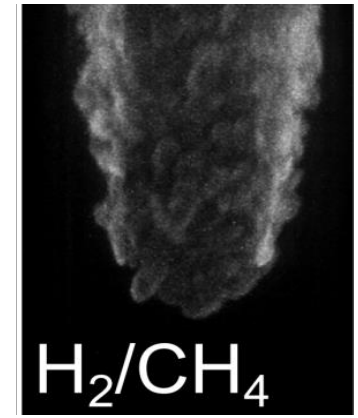
Matched laminar flame speeds

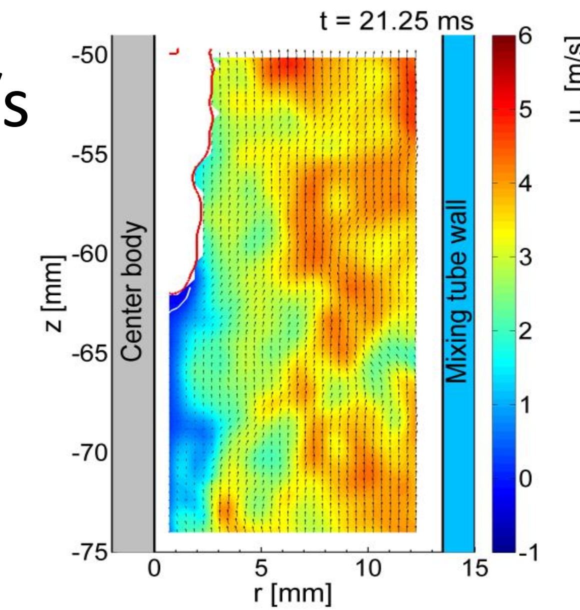
1 atm

CH_4-air
ϕ = 0.8,
T_{ad}=2000K
Re_h=5,000
S_L=0.26 m/s



H_2-air
ϕ = 0.4,
T_{ad}=1400K
Re_h=5,000
S_L=0.26 m/s



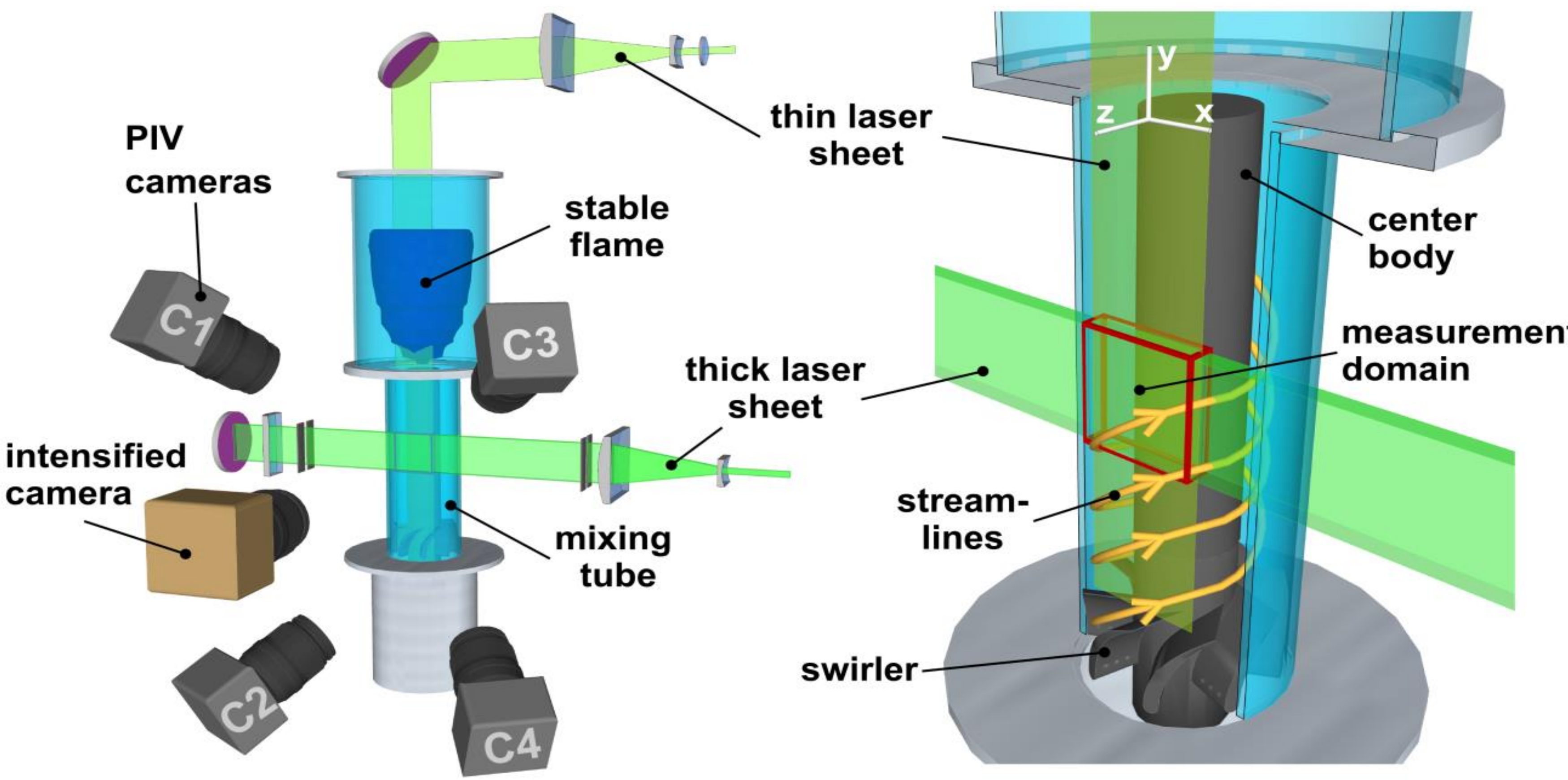


3D Measurements
CH_4-air Flames
Pressure: 1 atm

High-speed tomographic PIV

- It is clear that fully 3D measurements of the complex flowfield would be beneficial

    ➔ Tomographic PIV – 3D velocity in a volume

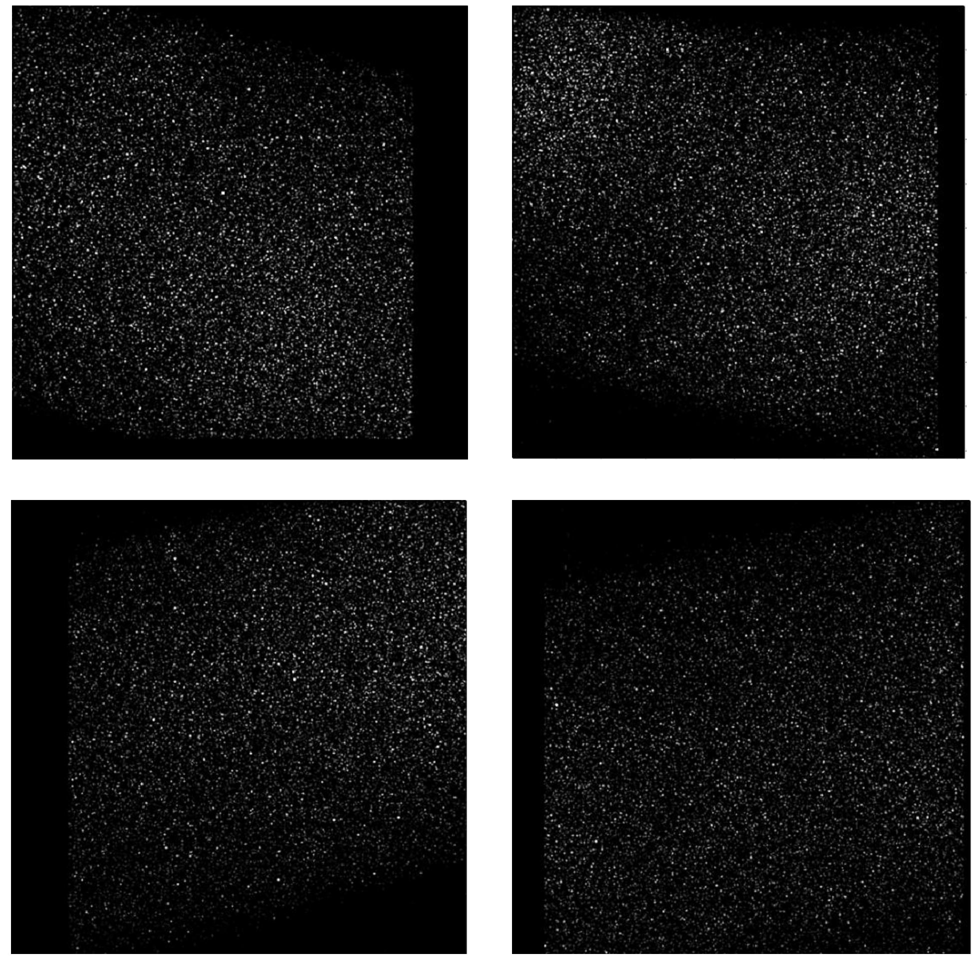


3D flame surface reconstruction

1. Raw images

2. Image preprocessing

Camera 1 Camera 2



Camera 3 Camera 4

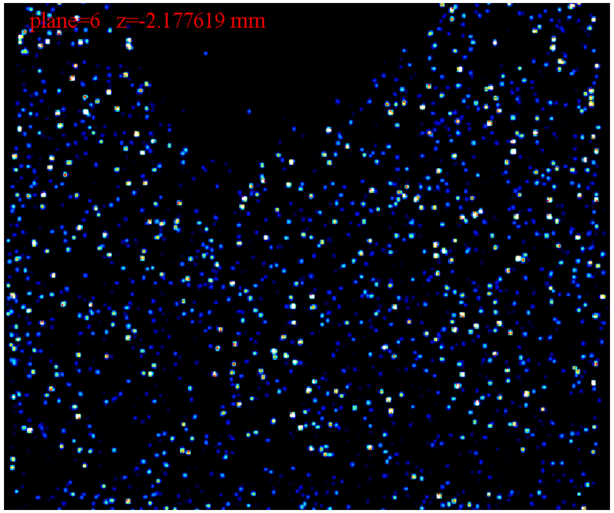
3D flame surface reconstruction

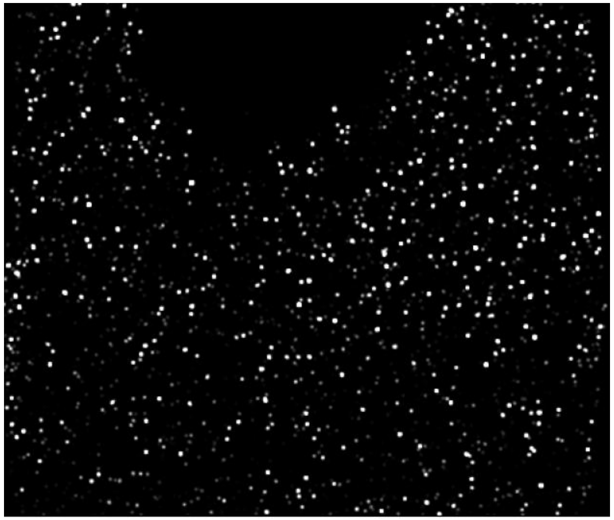
1. Raw images

2. Image preprocessing

3. Reconstruction of 3D-particle field

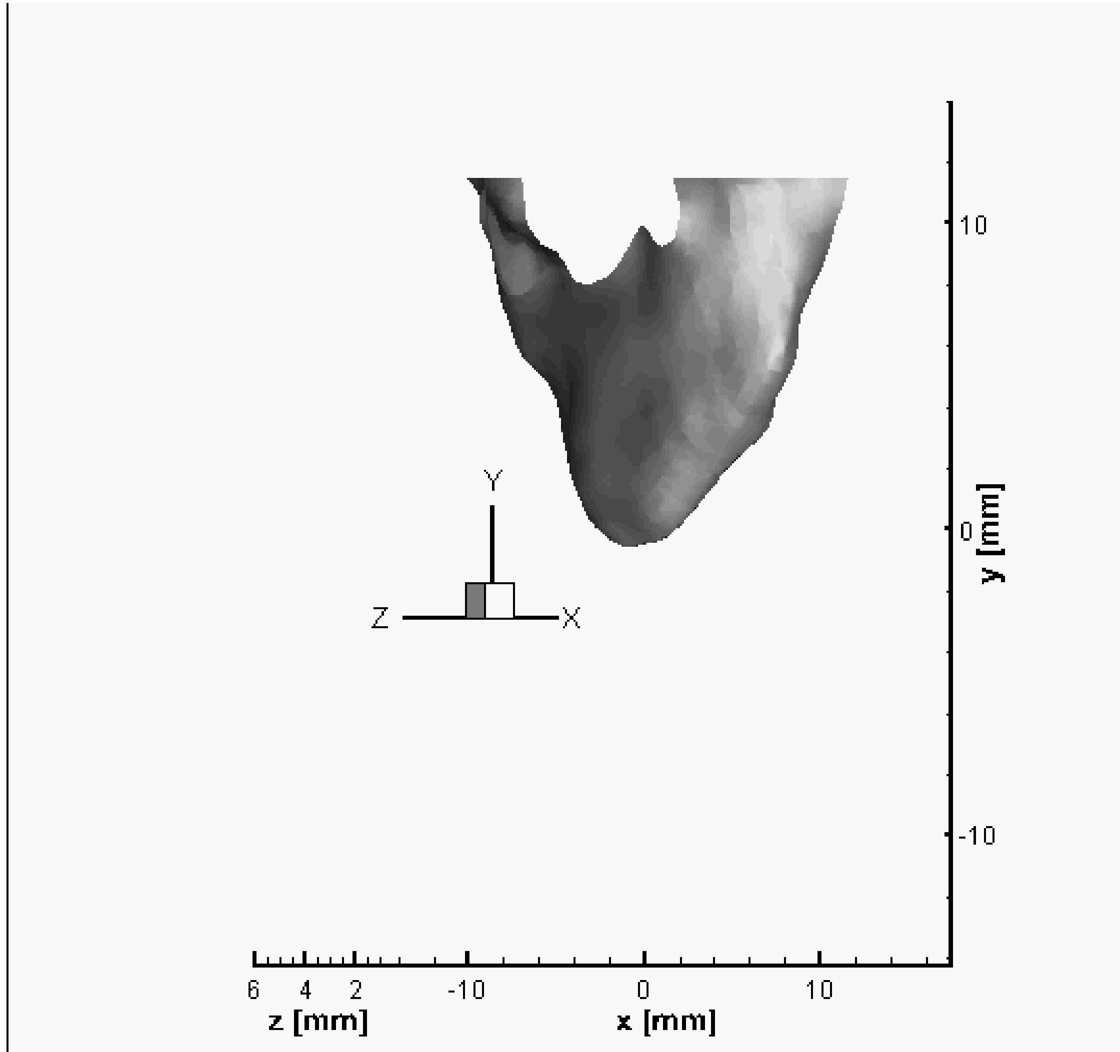
4. Determining interrogation volumes occupied by flame



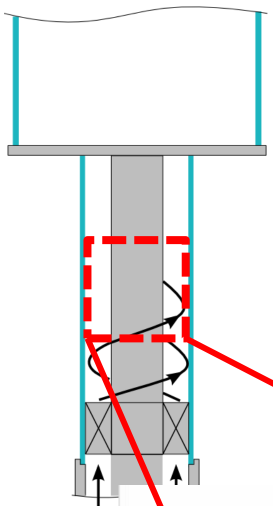


3D flame surface reconstruction

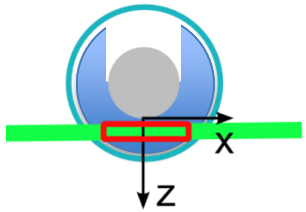
- We have developed a new method to reconstruct the 3D flame surface
- Uses tomographic reconstruction of aerosol particles
- Method gives flame surface + velocity field at 4kHz

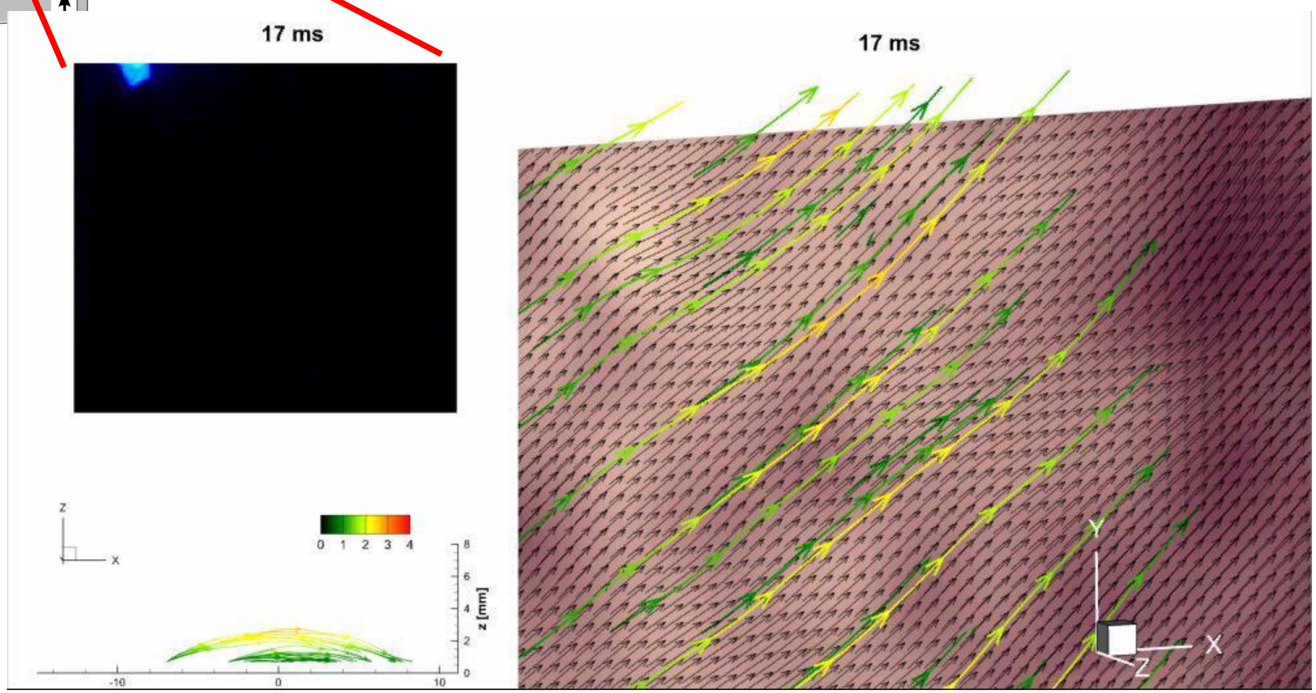


Time-resolved 3D flow-flame interaction



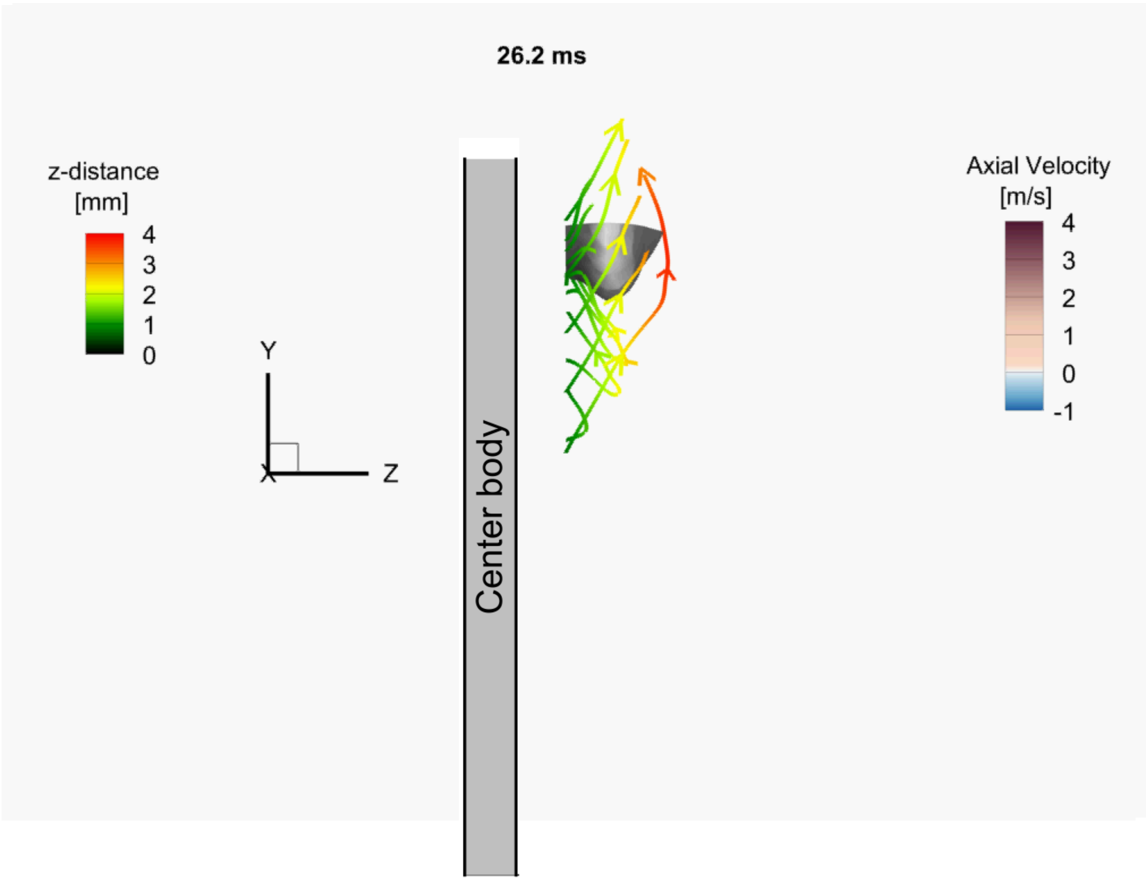
top view:





Effect of flame on approach flow

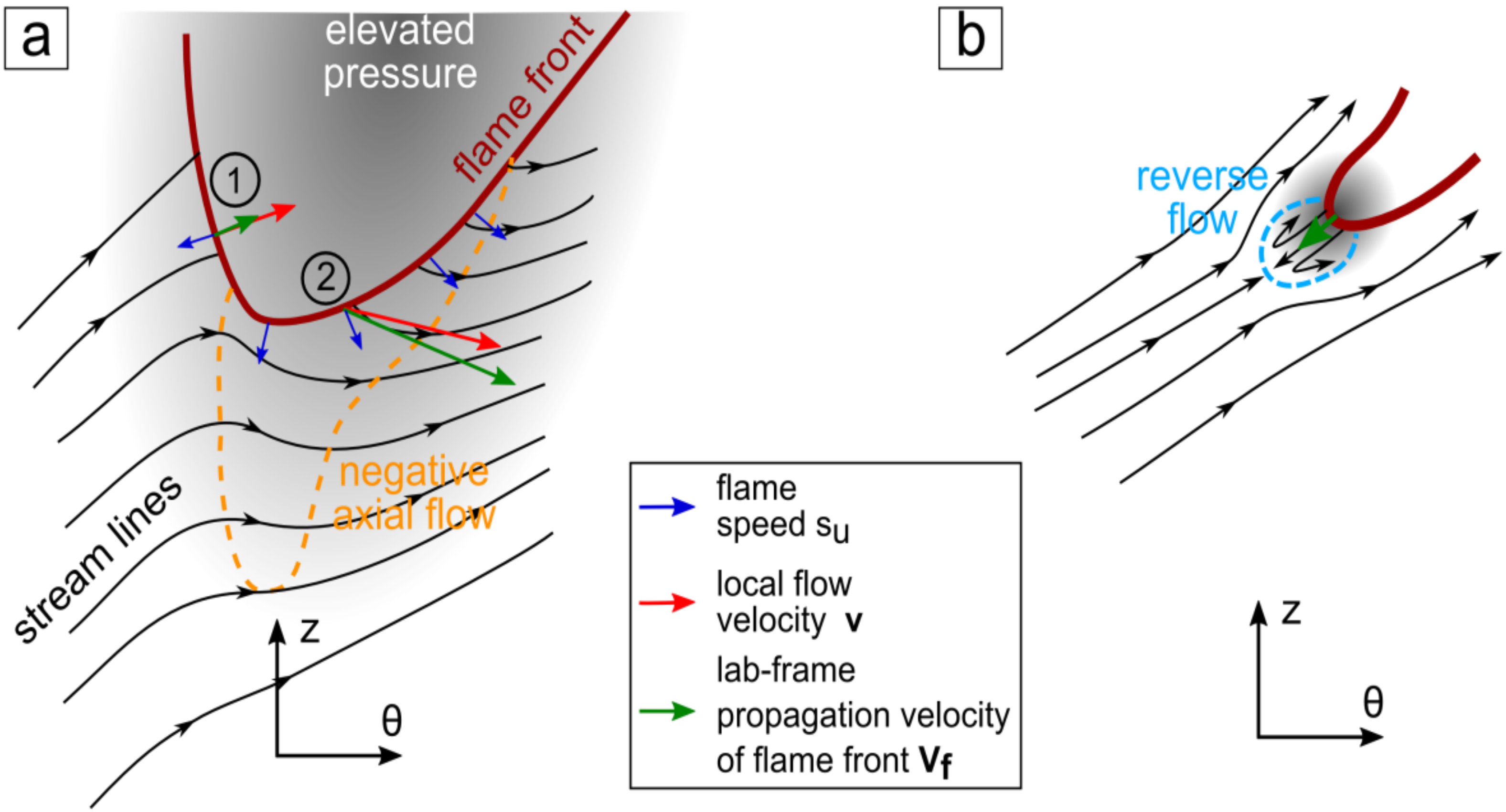
3D displacement of streamlines



Summary of upstream flame propagation

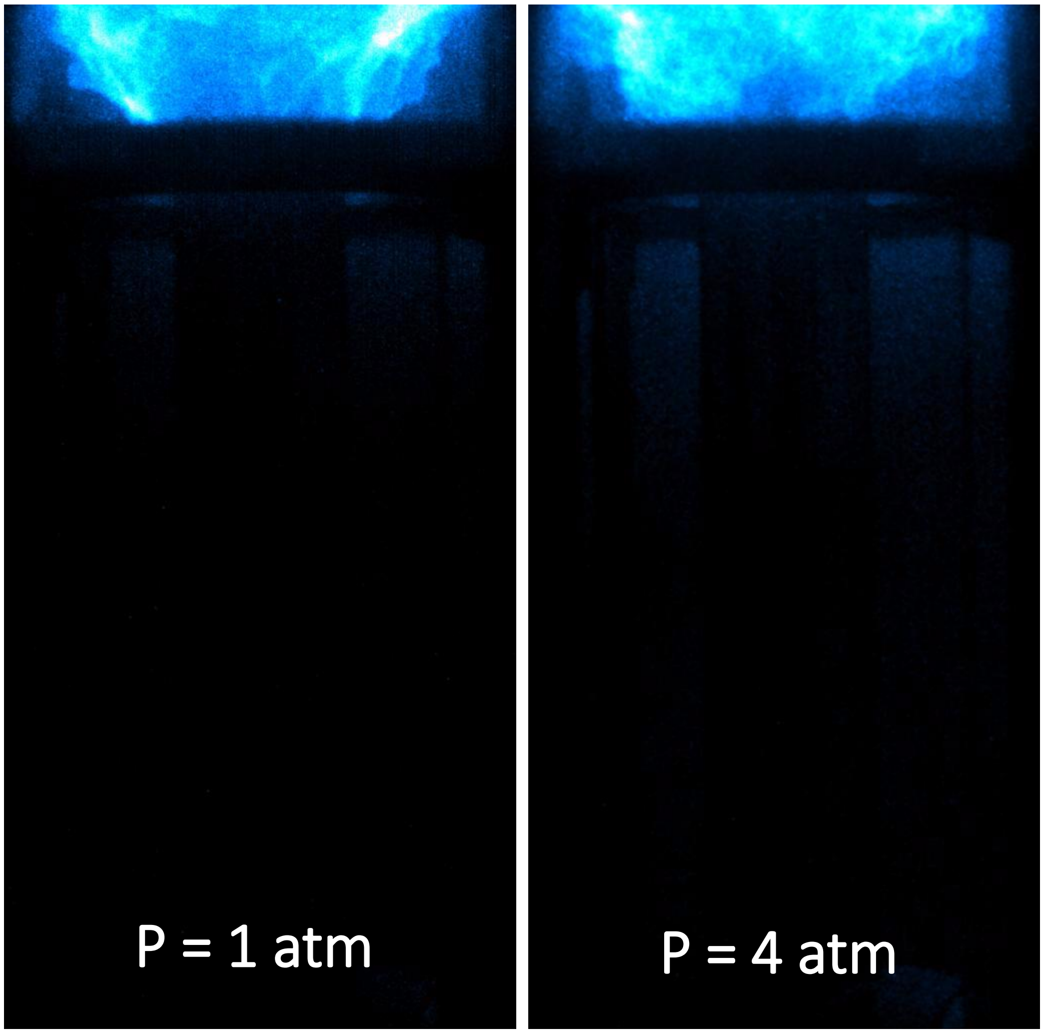
Flame Tongues

Flame Bulges



Flashback experiments at pressures up to 5 atm

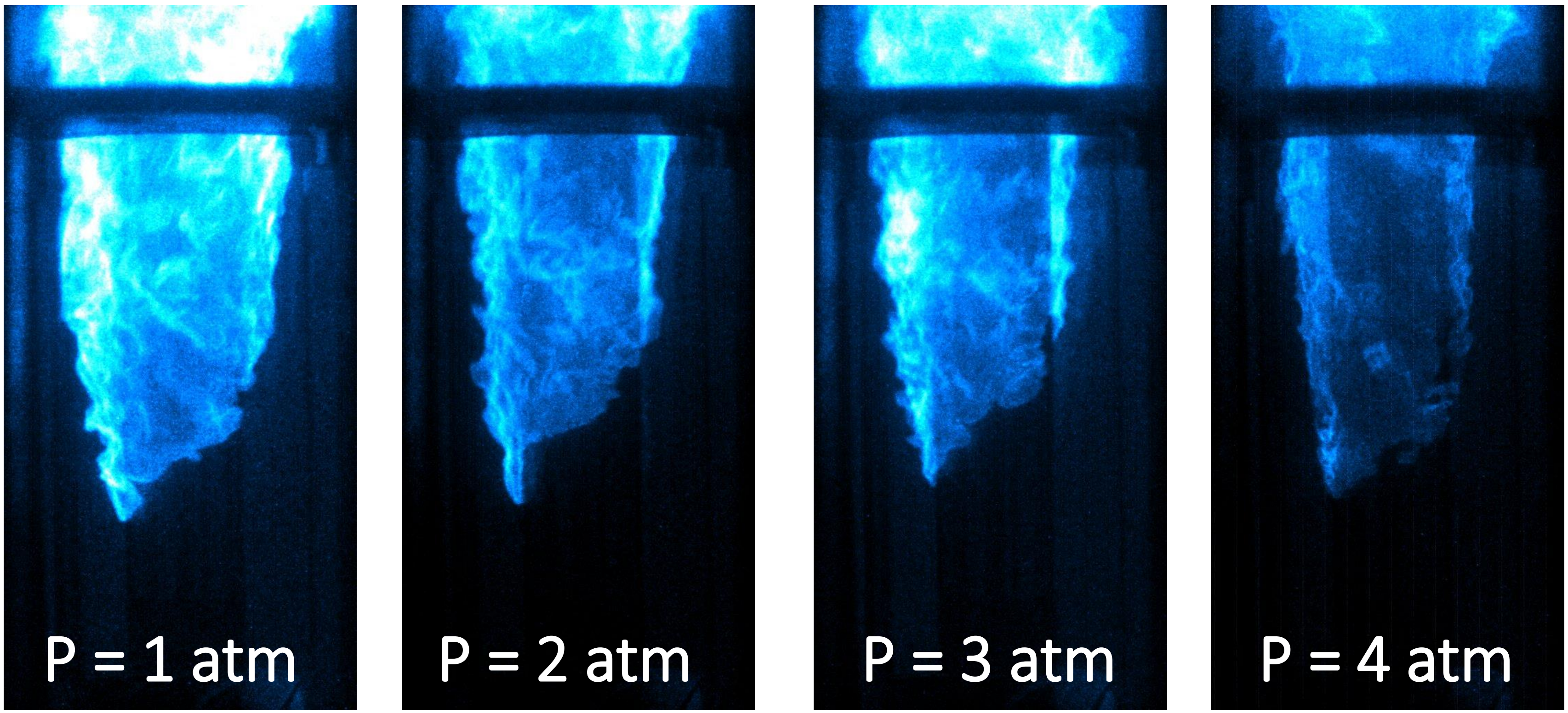
CH_4-air flashback at 1 atm and 4 atm



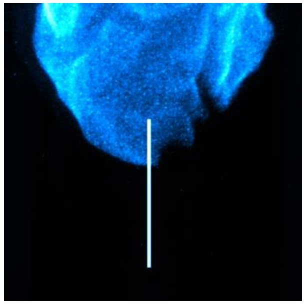
- Equal volume flow rate
- Increased flame wrinkling
- Less flame spread (remains closer to centerbody)

Flashback at different pressures

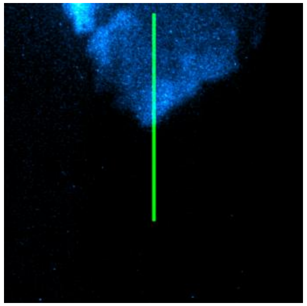
Maintain same average volume flow rate
Average axial velocity of 2.2 m/s



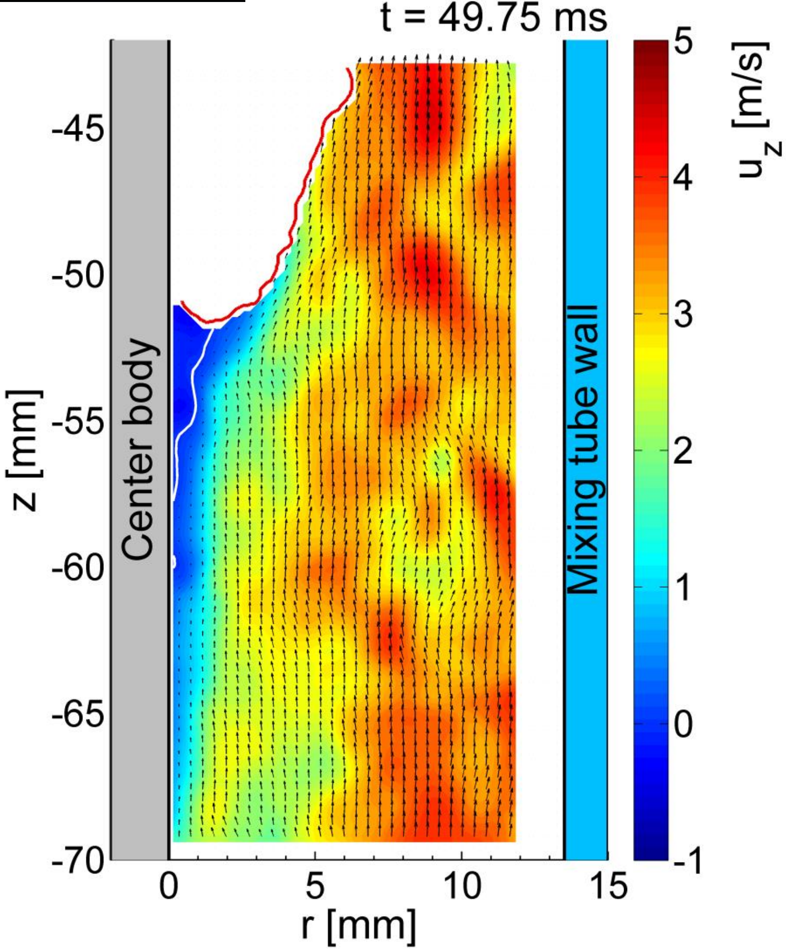
Effect of pressure on flame shape

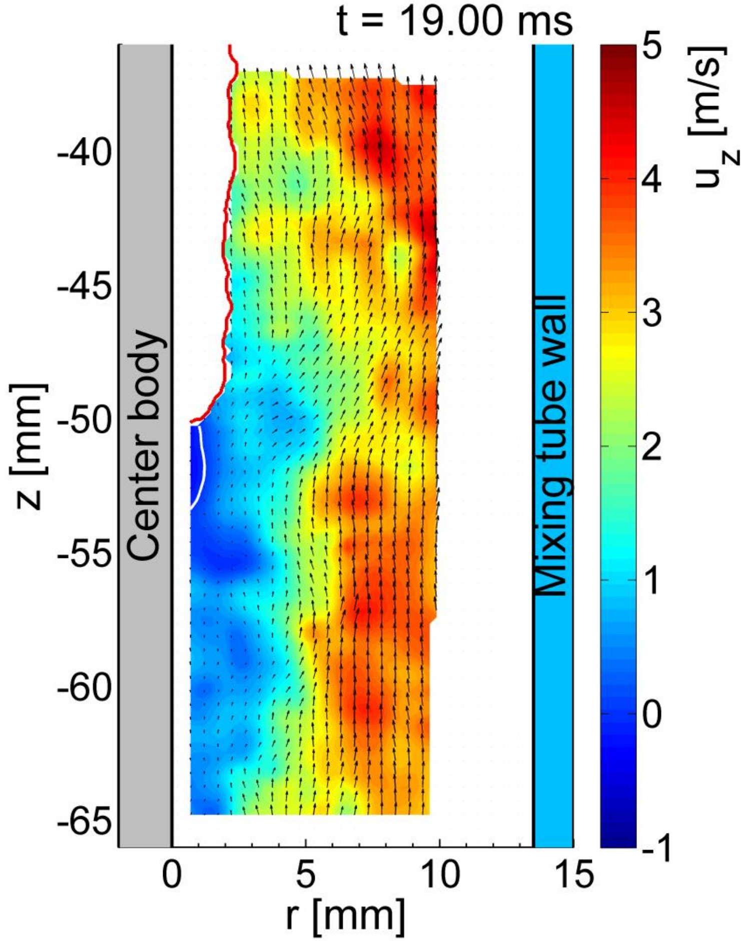


1 atm

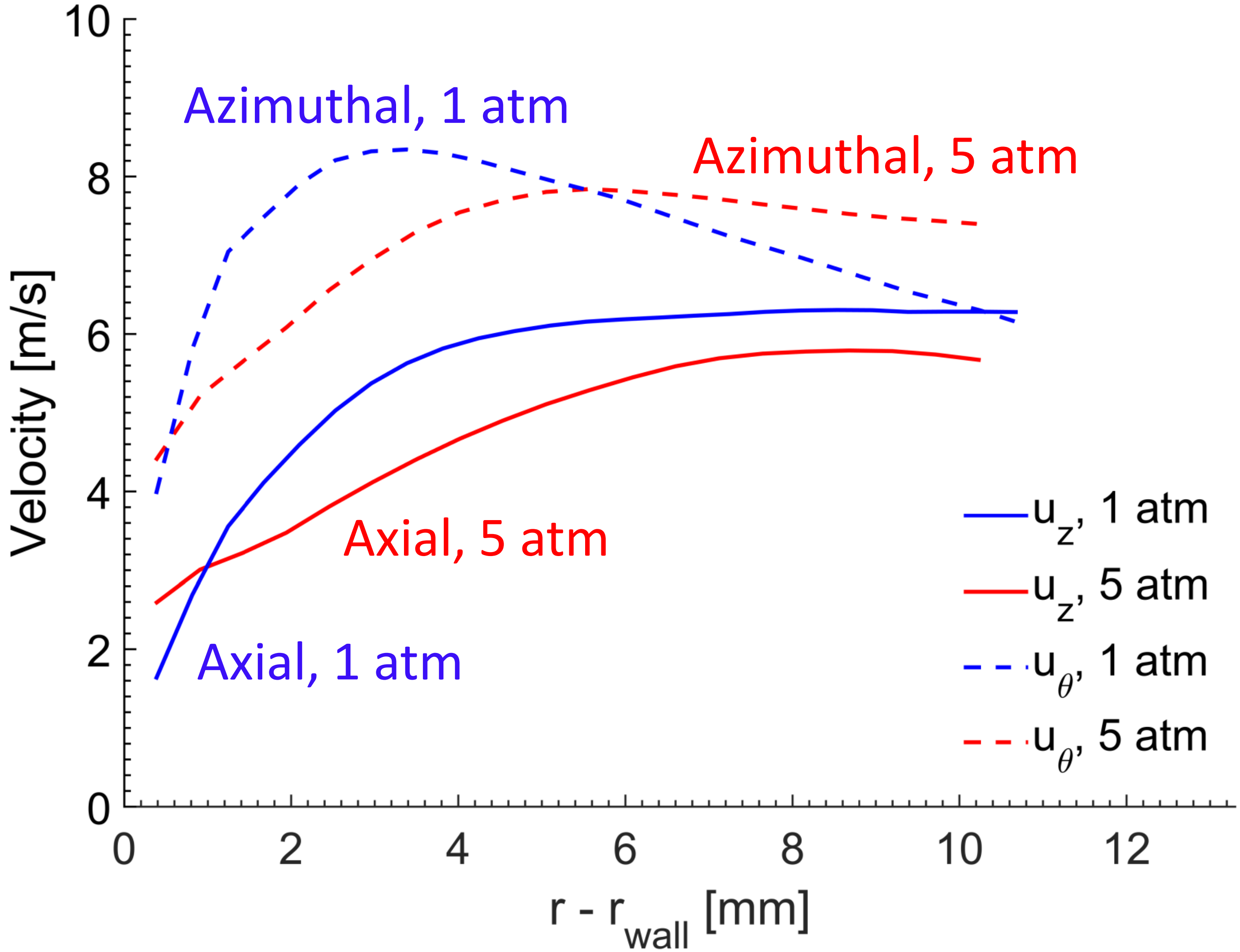


5 atm





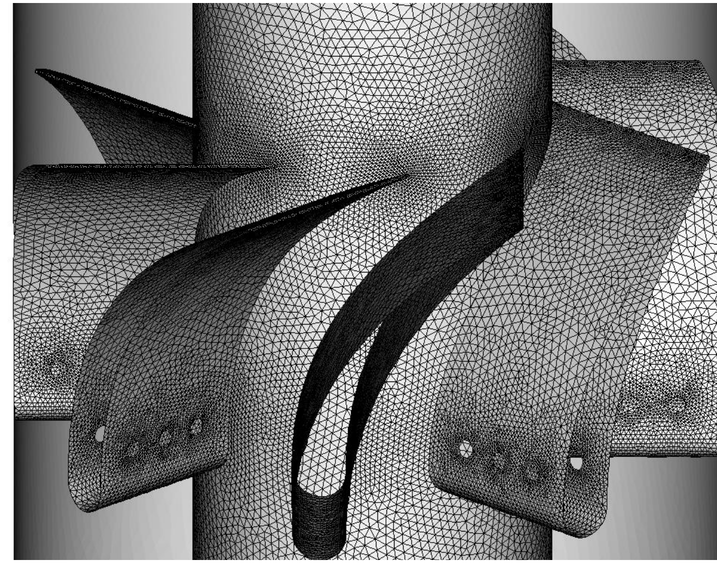
Effect of pressure mean velocity profiles

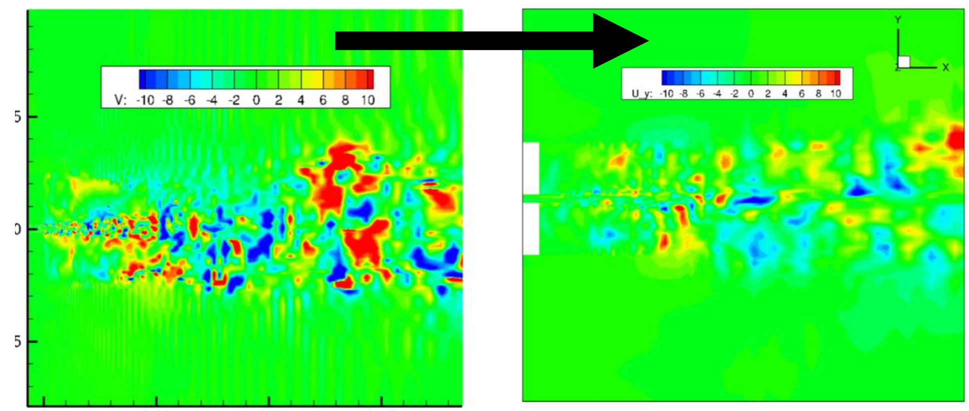


Large-Eddy Simulation Results

Swirler Flow Calculations

- LES computations in complex geometry
- Maintaining turbulent flow structures is non-trivial
  - Discrete kinetic energy conservation needed
- OpenFOAM collocated minimal dissipation solver
  - Developed at UM
  - Available as part of UM gas turbine simulation package



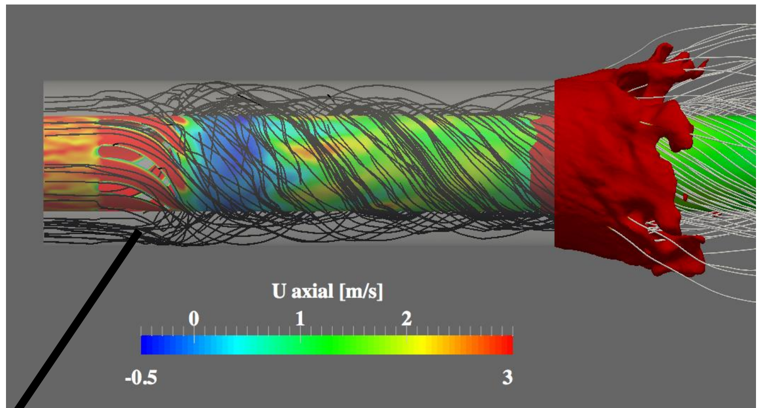


Radial velocity in bluff body jet **with** kinetic energy conservation

Radial velocity in bluff body jet **without** kinetic energy conservation

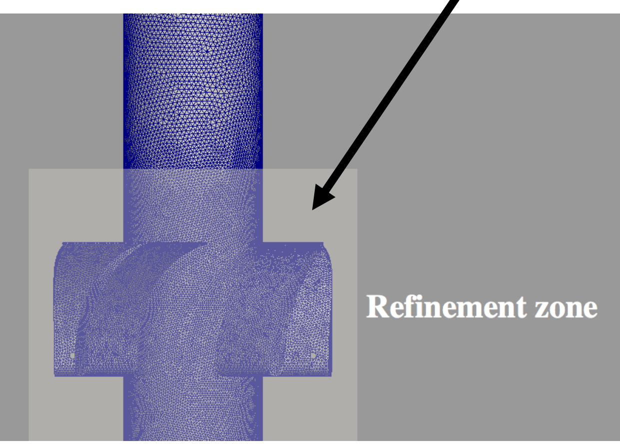
Swirler Computations

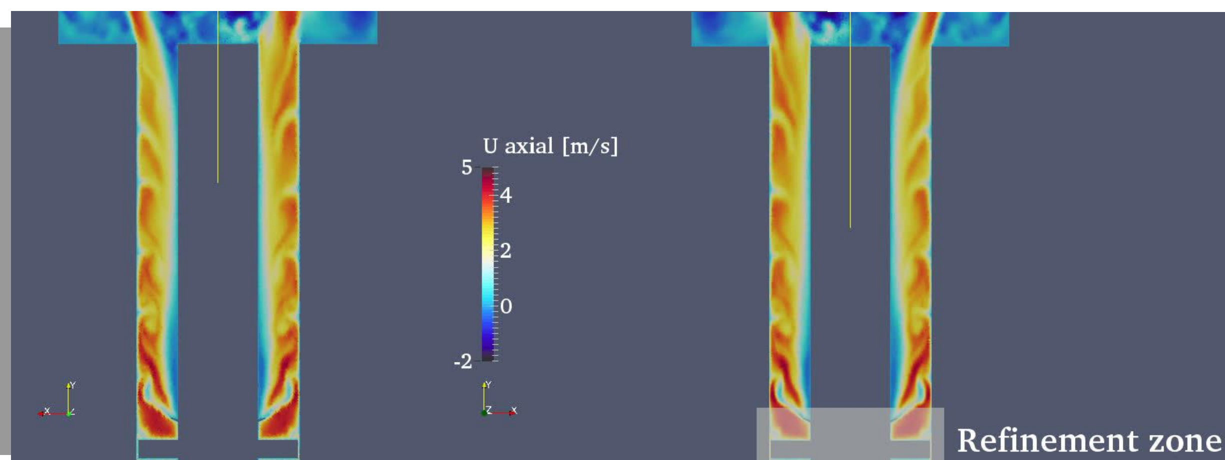
- Swirl vanes are sources of unsteady vortex shedding
  - Capturing these structures is critical



8M cells (no refinement)

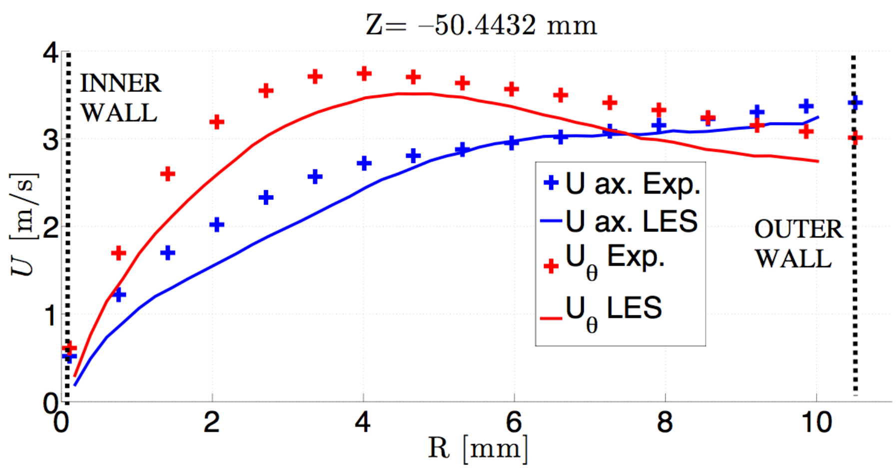
12M cells



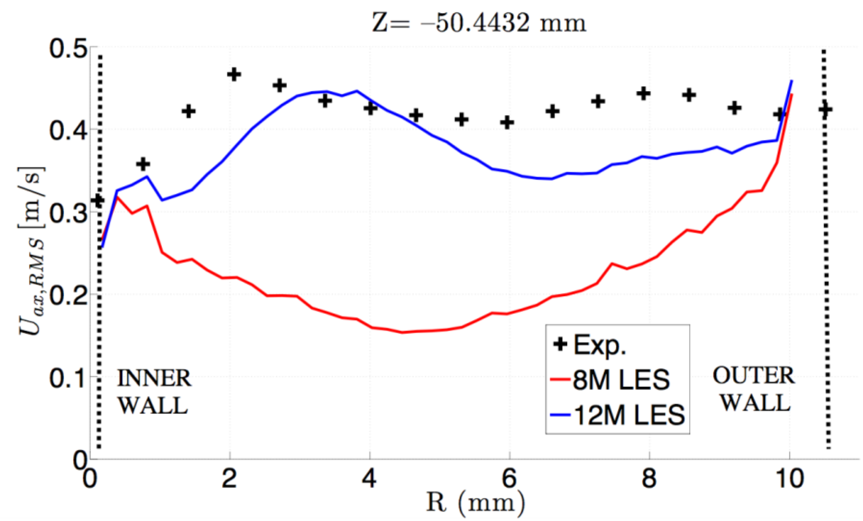


Non-reacting Flow Statistics

Mean/Azimuthal Axial Velocity



RMS Axial Velocity (grid convergence)

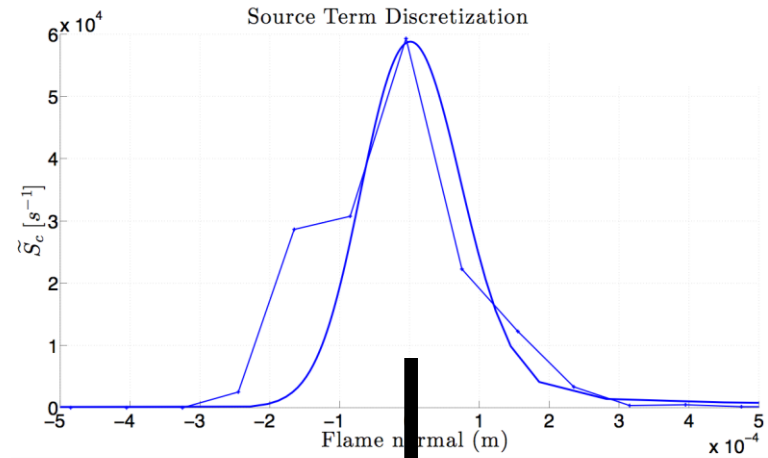


- Mean velocity insensitive to grid size
  - RMS velocities require much higher resolution to capture vane-generated turbulence
  - Similar results at all axial positions

Reacting flow simulations

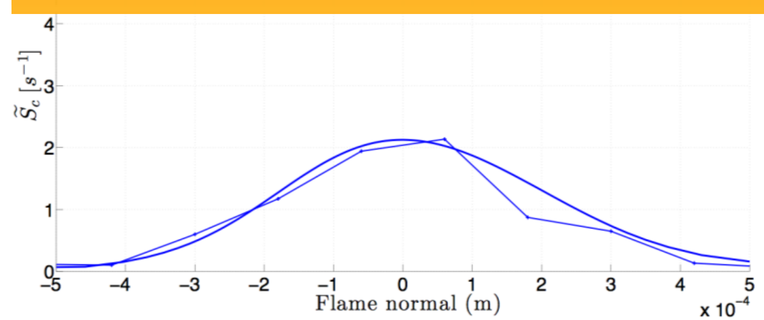
- Filtered-tabulated chemistry model
  - Wrinkling factor added to model sub-grid flame structure
- Filter size of 0.5 mm
- Grid size from 0.4 to 1 mm
  - Note that filter size is enforced using a filtered chemistry model
- This approach provides a natural transition to stratified flames

FLAMELET SOURCE TERM



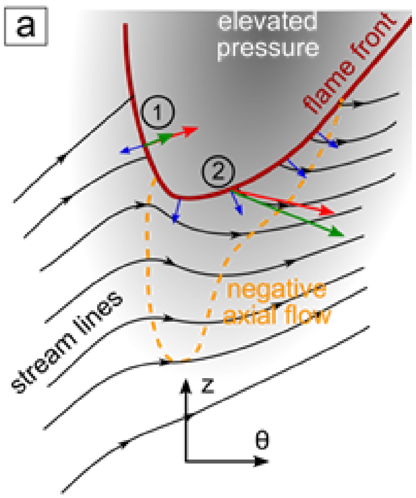
Lines denote different grid-to-filter ratio

FILTERED SOURCE TERM



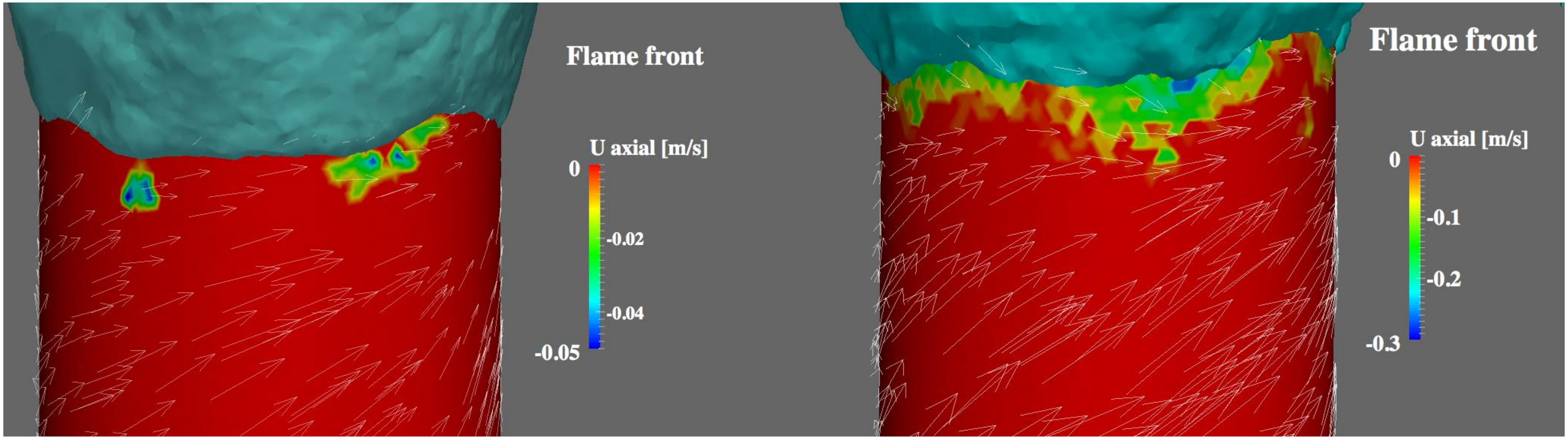
Stable flame configurations

- Blockage effect induced by the flame creates upstream reverse flow pockets
- The effect is enhanced at high pressure



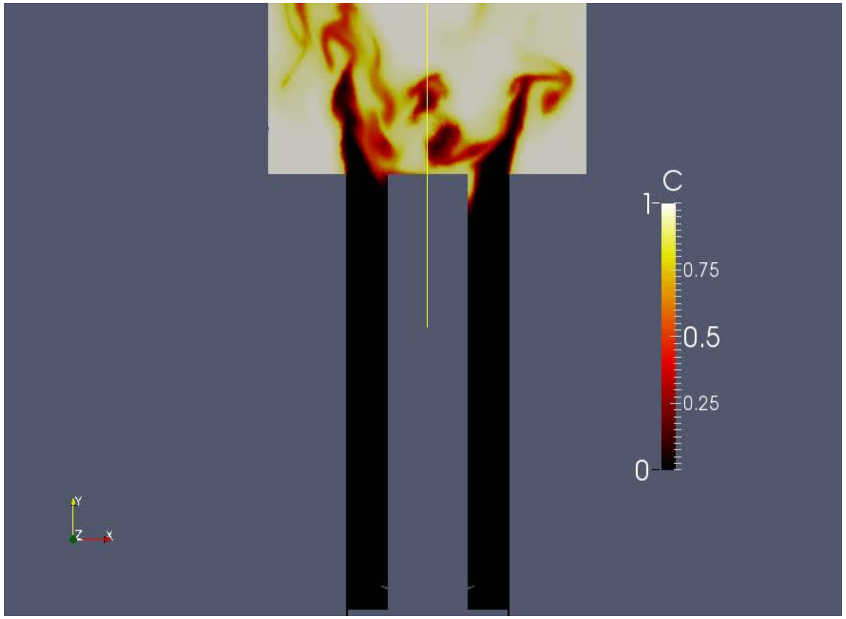
1 ATM/CH4

4 ATM/CH4

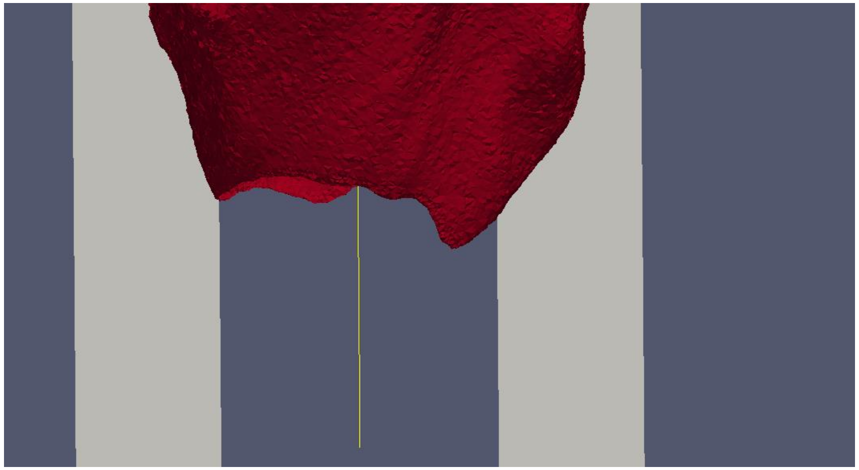


Flame topology during flashback

- Flame front more uniform in azimuthal direction
- Flame tongue appears only when flashback is triggered
- Both observations differ from experimental data



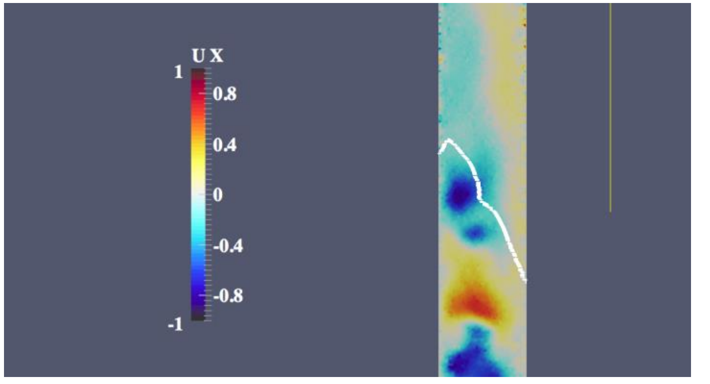
ISOCONTOUR OF EQUIVALENCE RATIO

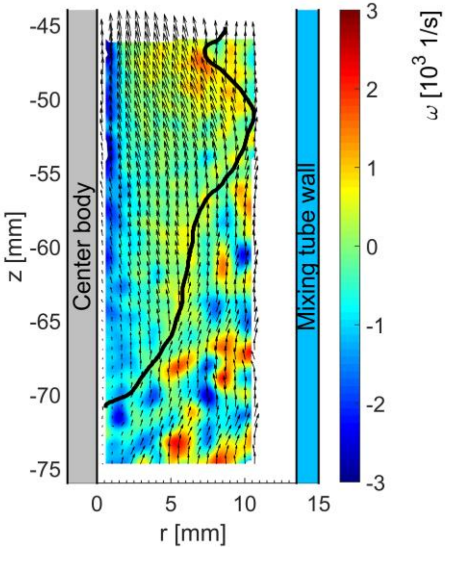


FLAME SURFACE

Flame 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
  - Low Mach number solver seems to spread out pressure disturbances over entire domain
- Are basic flow assumptions not valid in unsteady confined flame motions?





Program Outcomes

- New 1-atm and high-pressure swirl-flame facilities have been constructed to enable study of flashback at a range of pressures
- Extensive measurements have been made of boundary layer flashback with varying
  - Reynolds number
  - Fuel composition (CH_4+H_2)
  - Pressure (1 to 5 atm)
- Used high-speed PIV and 3D flame surface imaging
- Measurements have provided new physical insight and proved valuable for LES model validation

Program Outcomes

- Developed a new flamelet approach for premixed flames with wall quenching
  - Targeted for boundary layer flashback
  - Validated using DNS data and experimental measurements
- Developed a minimally dissipative collocated numerical scheme for unstructured grids
  - Implemented and verified in OpenFOAM open source package
  - Adapted for industrial use, and validated in complex geometry test cases
- Identified potential shortcomings
  - Low Ma assumption may not produce flashback flame structure
  - Pressure effects might be transient in nature

END