Large Eddy Simulation Modeling and Experiments of Flashback and Flame Stabilization in Hydrogen-rich Gas Turbines

DE-FE0007107

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Background

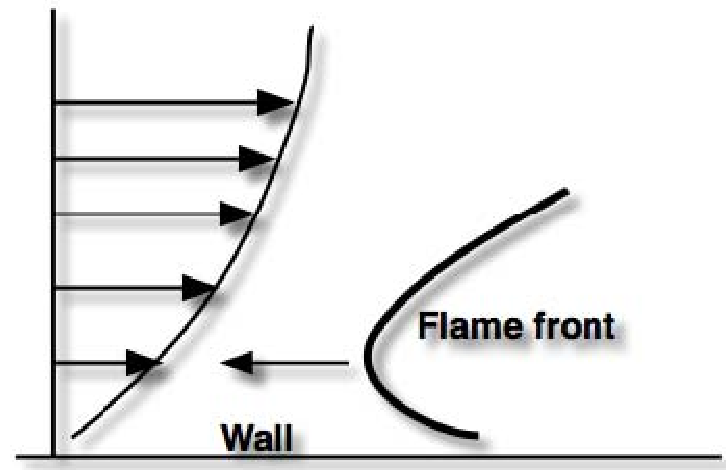
- Focus on syngas based combustion in gas turbines
- Hydrogen in fuel
  - → Increases fuel reactivity
  - → Alters the flame location and dynamics compared to natural gas combustors
    - Increased volumetric flow rate
    - Higher reactivity
  - → How does hydrogen change flame dynamics?
- Specific focus on flame flashback in gas turbines

Flashback in Gas Turbines

- Gas turbines operate in premixed combustion mode
  - → Fuel and compressed air mixed prior to entering combustion chamber
- Fuel mixing carried out in premixing chamber
- Flashback
  - → Flame in main combustor moves inside premixing chamber
  - → Catastrophic consequence since premixer cannot hold high temperature flame
- Hydrogen increases chance of flashback
  - → Higher reactivity causes flame to move back

Boundary Layer Flashback

- Many different flashback modes possible
- Hydrogen-based combustion dominated by boundary layer flashback
- Flow near wall is slower than flame speed
  - → Flame propagates upstream
  - → Only wall quenching arrests flame
- Unique physics affects modeling
  - → Turbulent boundary layer affecting flame physics



Project Outline

- Experimental program
  - Understand flashback physics
  - Effect of fuel variation on flame propagation
- Large eddy simulation (LES) based modeling
  - Proven to be accurate for other combustion problems
  - Understand capabilities for boundary-layer flame interactions
- Interaction with industry
  - OpenFOAM based model transfer
  - Experimental design based on inputs from GE and Siemens Inc.

Ancillary Topics of Research

- Over three years, multiple side topics were considered
  - Uncertainty quantification of chemistry models
    - To understand the accuracy of flame speed results
  - Adjoint-based sensitivity of chemistry models
    - To determine the most critical modeling parameters
  - Simulation of canonical flames and DLR combustor
    - To aid Siemens Inc. in the incorporation of combustion models
  - Simulation of Georgia Tech. Univ. JICF configuration
    - To aid Siemens Inc. in the testing of basic combustion models

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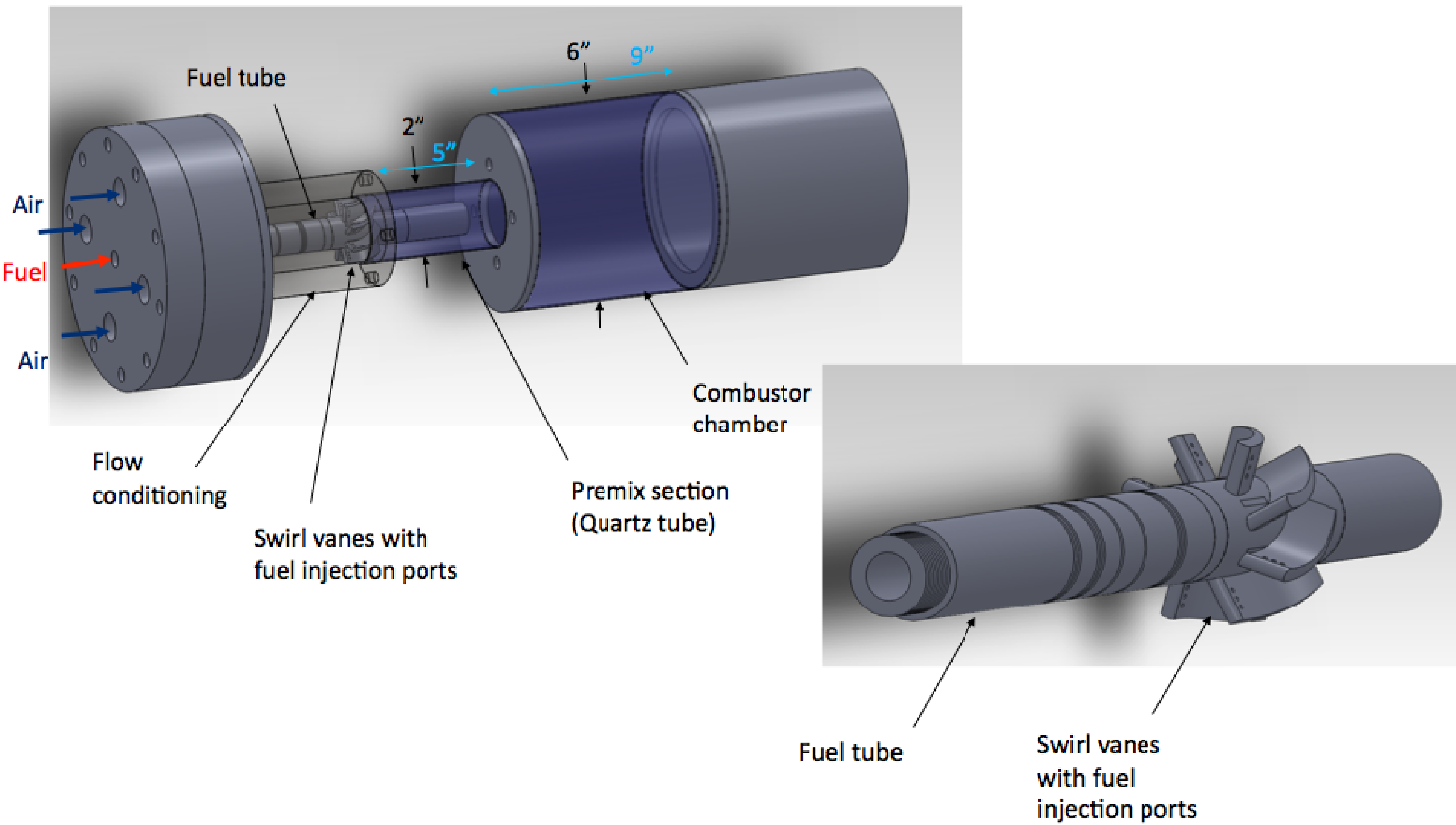
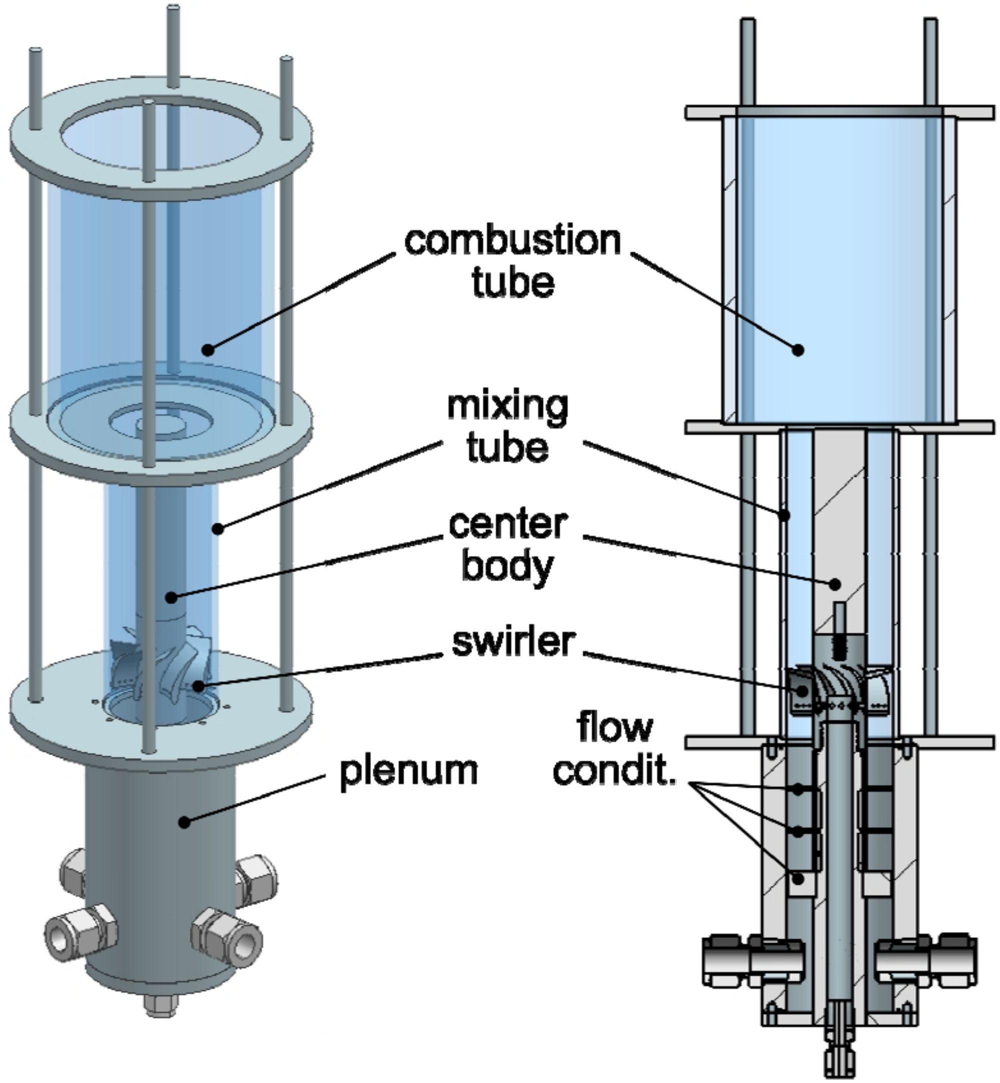
UT Swirl Burner

- UT high-pressure swirl combustor

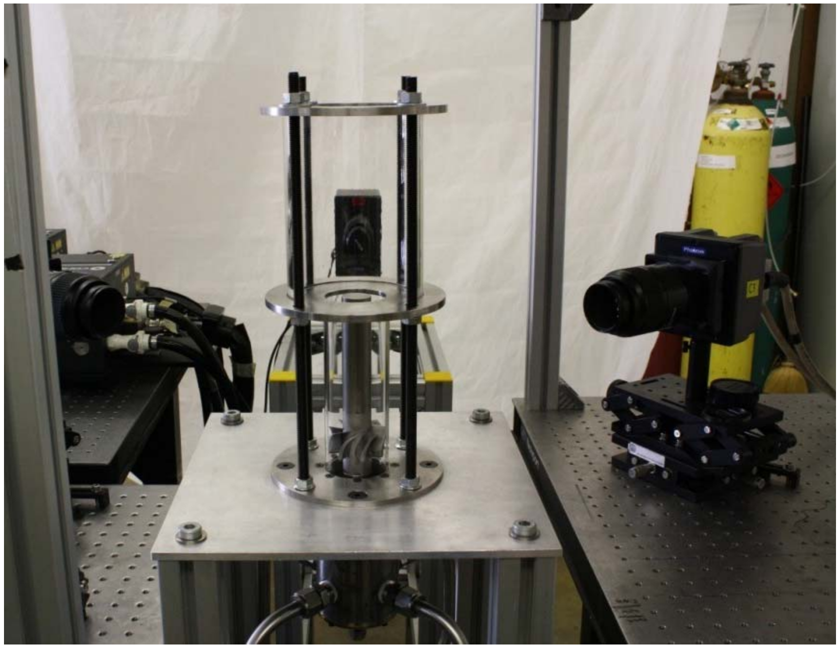


Confined Model Swirl Combustor

- Single axial swirler
- Swirl number: S ≈ 0.9
- Two types of fuel mixing:
  - → Fully premixed upstream of plenum
  - → Fuel injection through ports in swirler vanes, mixing in mixing tube

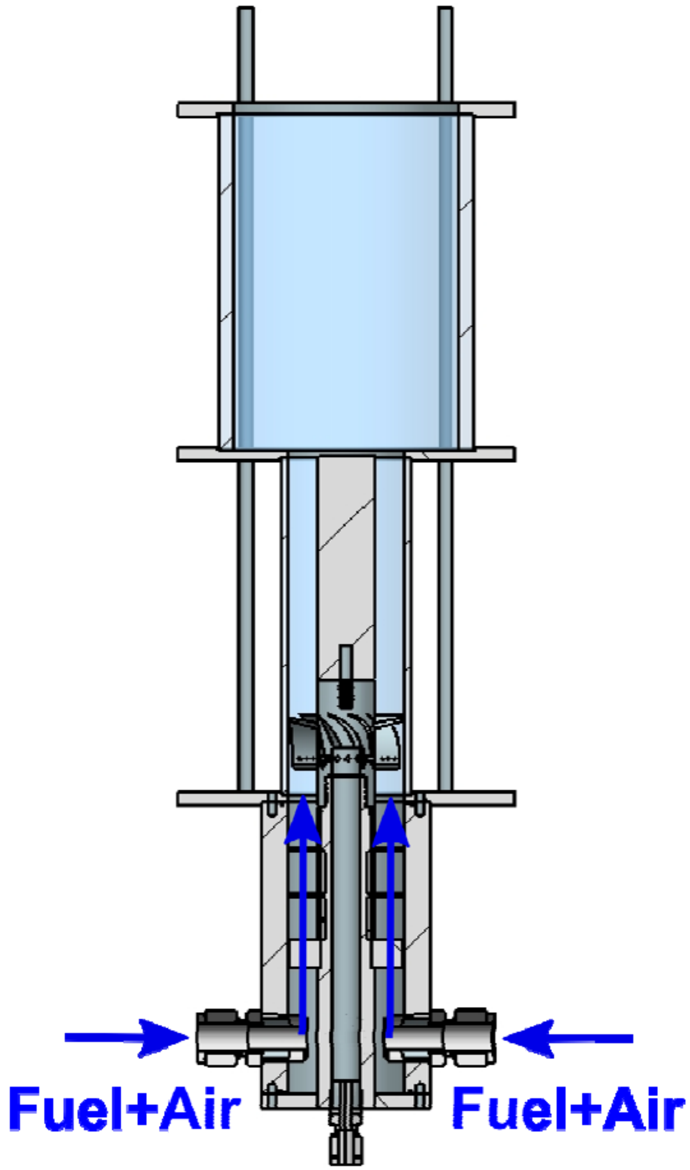


Experimental Setup



Experimental Conditions

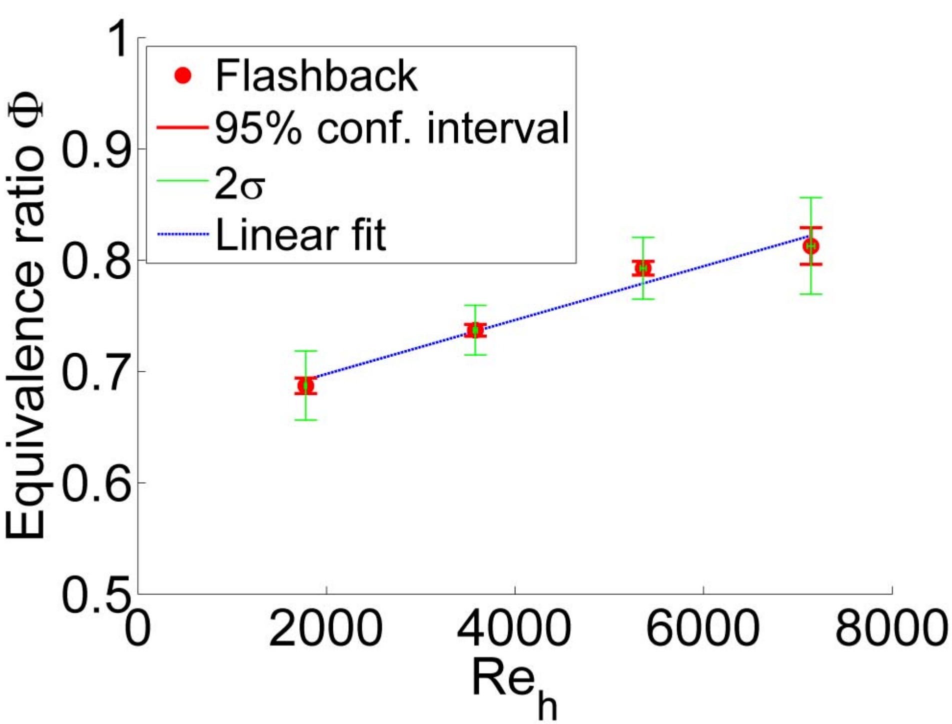
- Air supply at room temperature and atmospheric pressure
- Flow rates: from 1m/s to 4m/s average axial velocity
- ReD ≈ 2,500 – 10,000
- Fuel: CH4/H2-mixtures, fully premixed
- Flashback triggering: increase in equivalence ratio



Triggering flashback experimentally

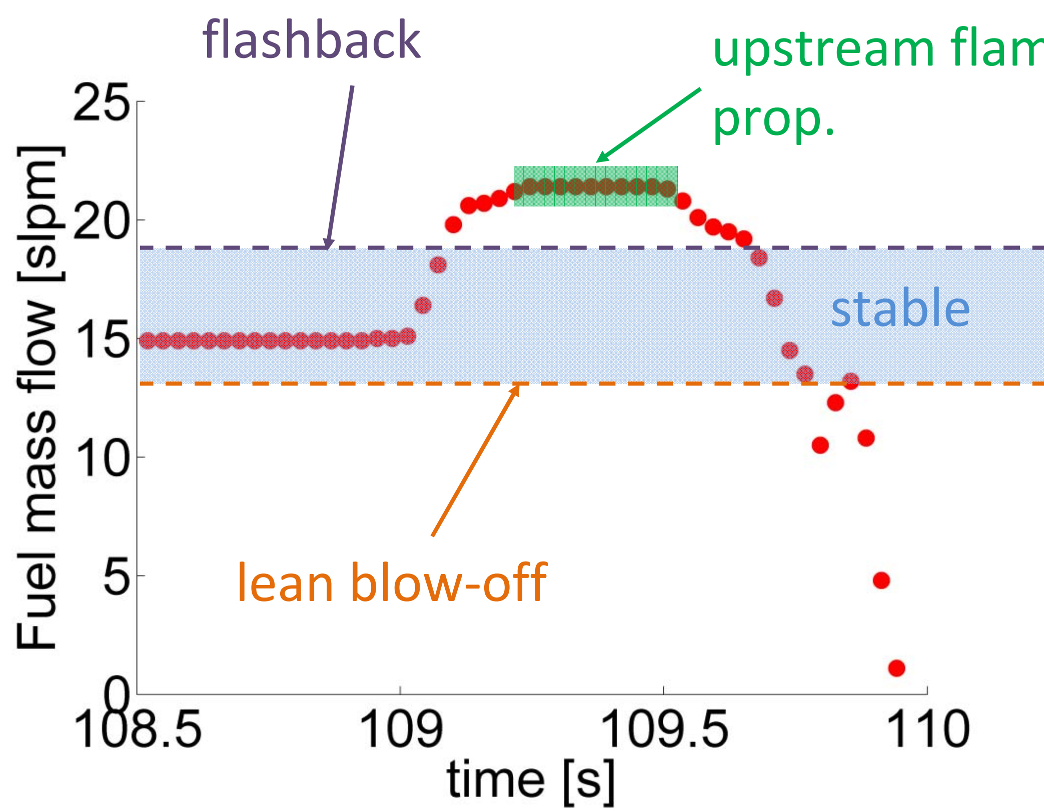
Method 1

- Slow increase in fuel flow rate
- Flashback at critical equivalence ratio



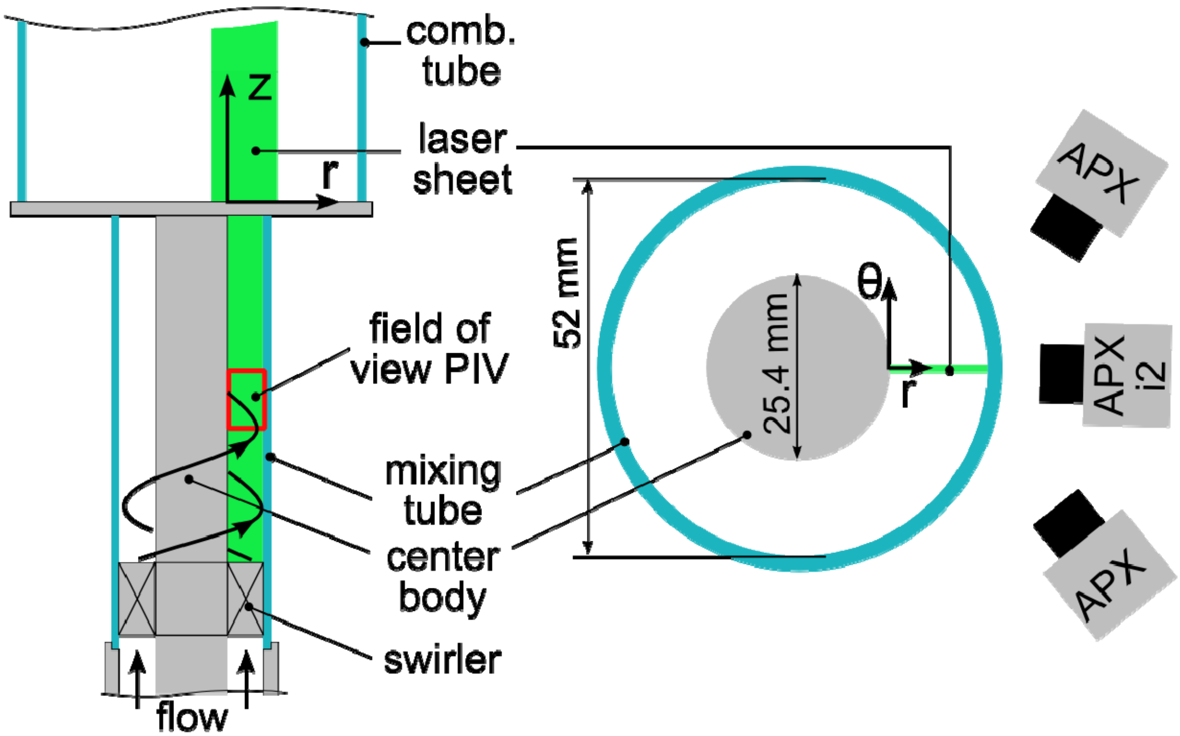
Method 2

- Step change in fuel mass flow
- Flashback at desired equivalence ratio

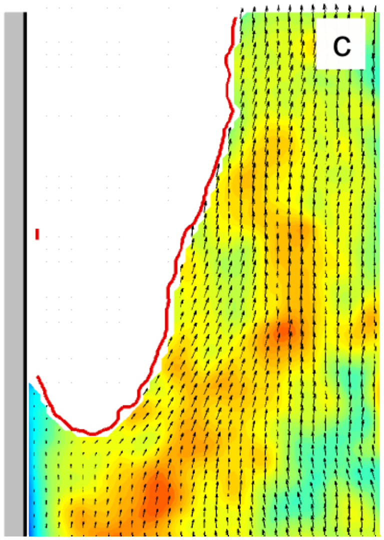


High-speed Imaging

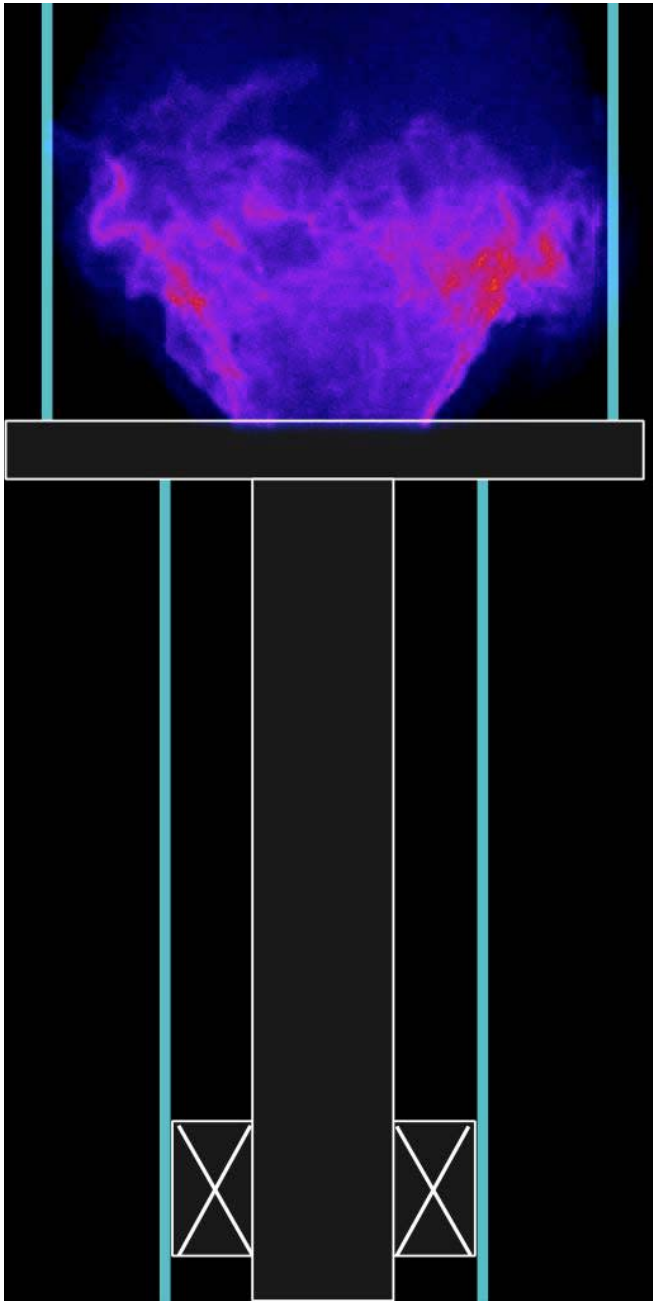
- Simultaneous 3-component (stereo-)PIV and flame luminescence imaging



Velocity measurements
all 3 velocity components in one plane
resolution:
temporal: 4 kHz
spatial: one vector every 0.4mm
Flame front detection based on vaporized seeding particles
luminescene at kHz rate



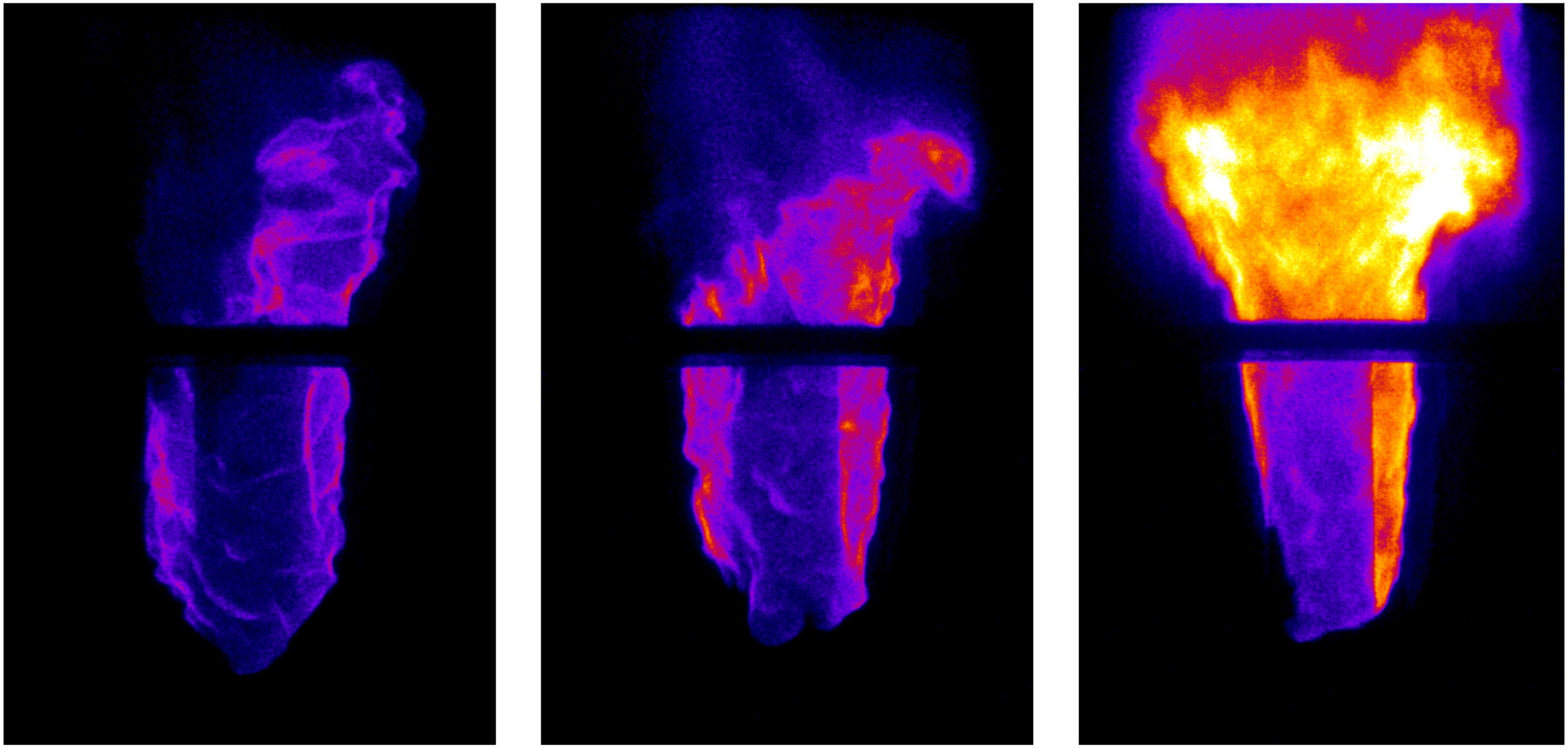
Typical Flashback



- High-speed chemiluminescence imaging
- Flashback along center body in swirling motion
- Flame stabilizies on trailing edges of swirler vanes
- Here: CH4-air at Re = 7200

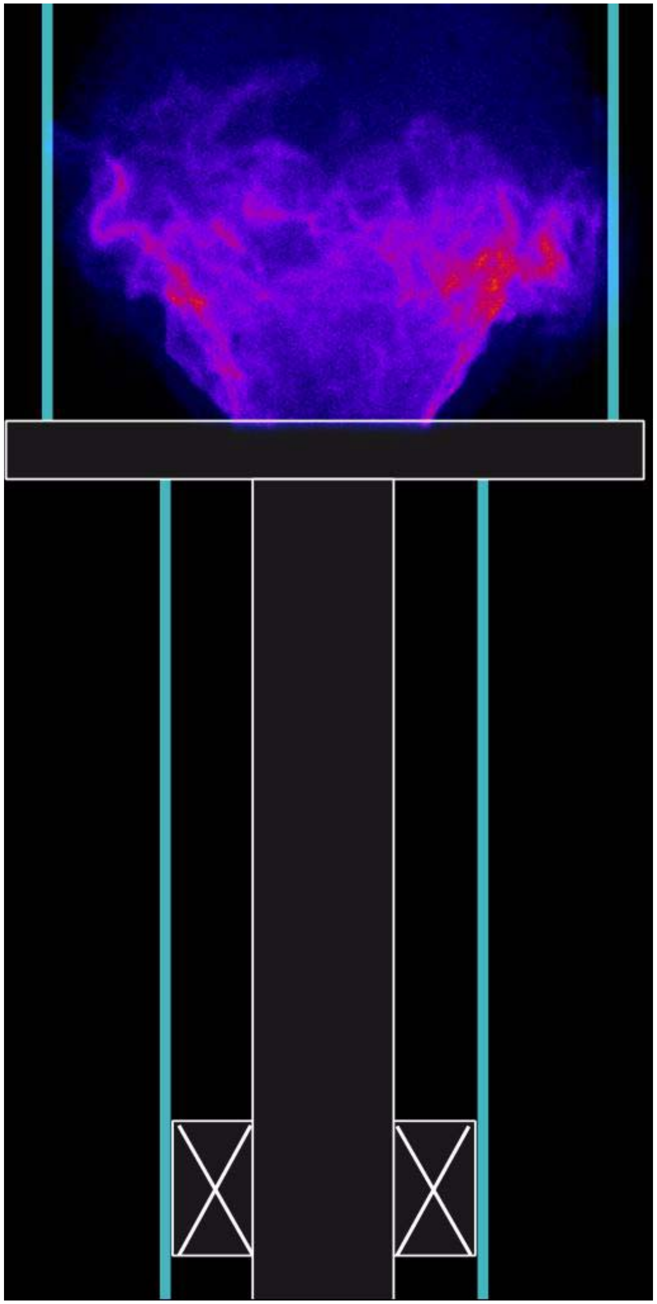
Effect of Reynolds Number

Re = 3600 Re = 7200 Re = 14400



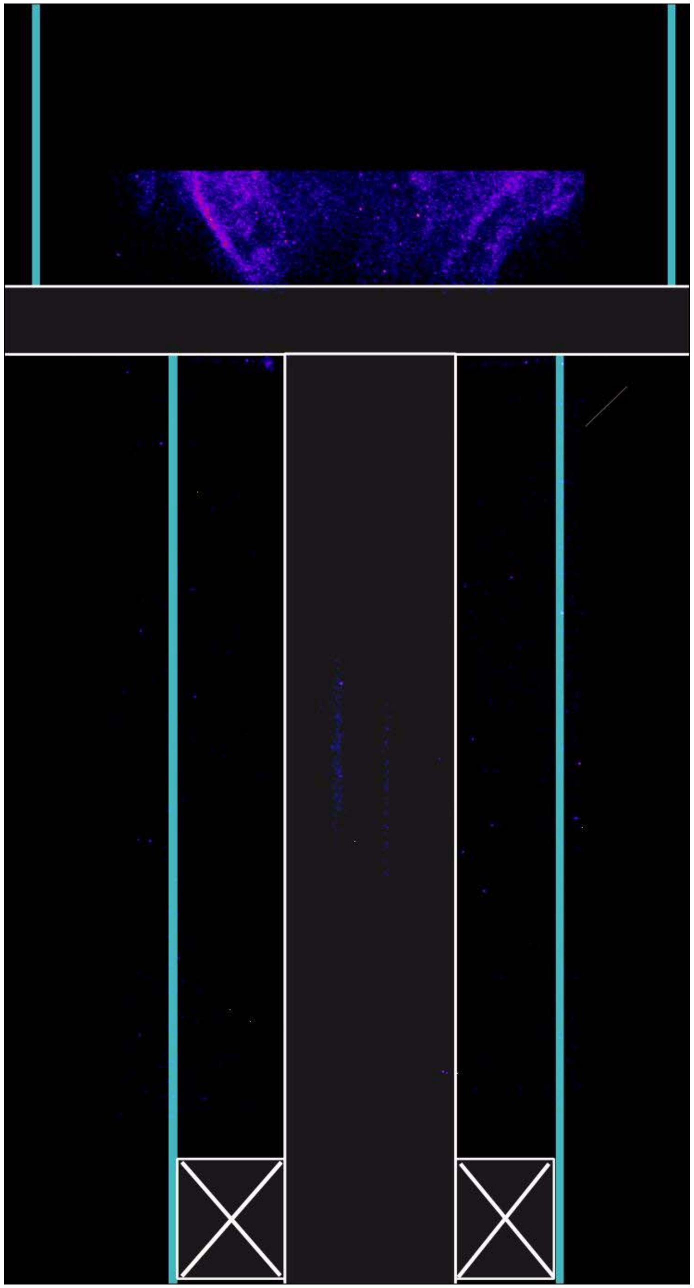
- All images taken at same framing rate
- Flame propagates faster at higher velocity -> structures are not as sharp

Global flashback behavior: CH_4-air flame



- High-speed chemiluminescence imaging (4 kHz)
- False color table applied to luminescence intensity
- Flashback along center body in swirling motion due to thicker boundary layer compared to outer wall
- One main flame tongue leading flashback

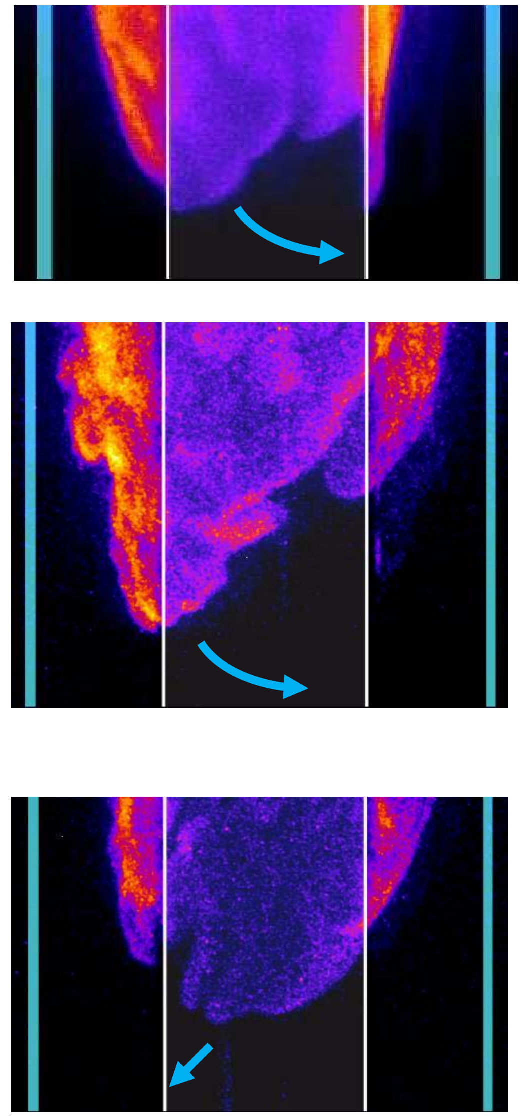
Global flashback behavior: H_2/CH_4-air flame (90% H_2 by vol.)



- Flashback again along center body
- Flame surface more convoluted due to non-unity Lewis number effects
- Upstream flame propagation: combination of large scale flame tongues convected in azimuthal direction with the flow and small scale flame cusps propagating against the undisturbed mean flow direction

Upstream flame propagation: Qualitative differences

- Mode 1 (“swirl flow flashback”)
  - → Flame tongues are convected by the flow in the azimuthal direction as they propagate upstream
  - → Found in both, CH4 and H2 flashback
- Mode 2 (“channel flow flashback”)
  - → Flame cusps convex towards reactants propagate upstream in the direction of the mean undisturbed flow
  - → Found in H2 flashback only
  - → Mechanism appears to be the same as in (non-swirling) channel boundary layer flashback

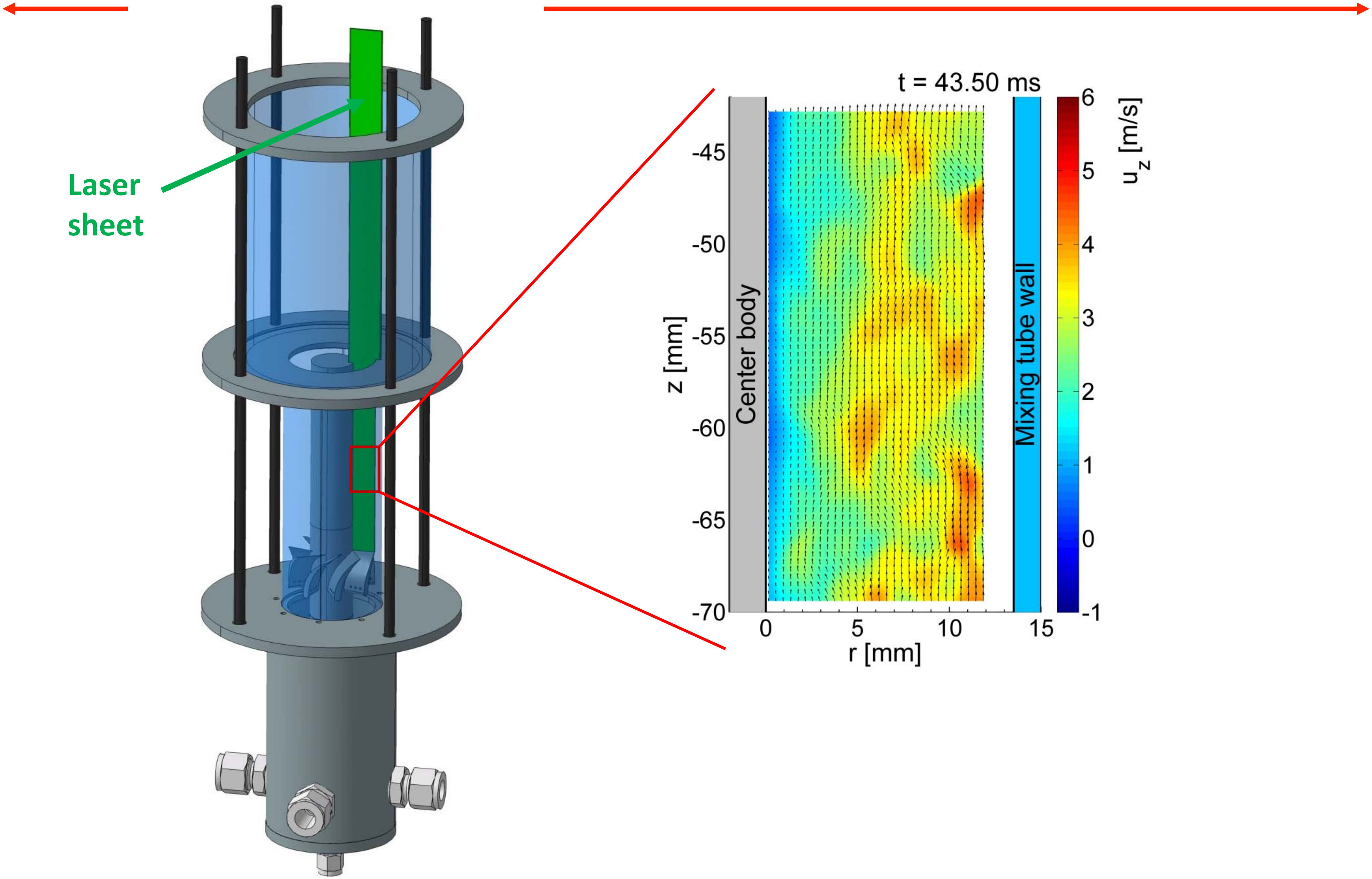


CH_4

H_2/CH_4 (90% H_2 by vol.)

H_2/CH_4 (90% H_2 by vol.)

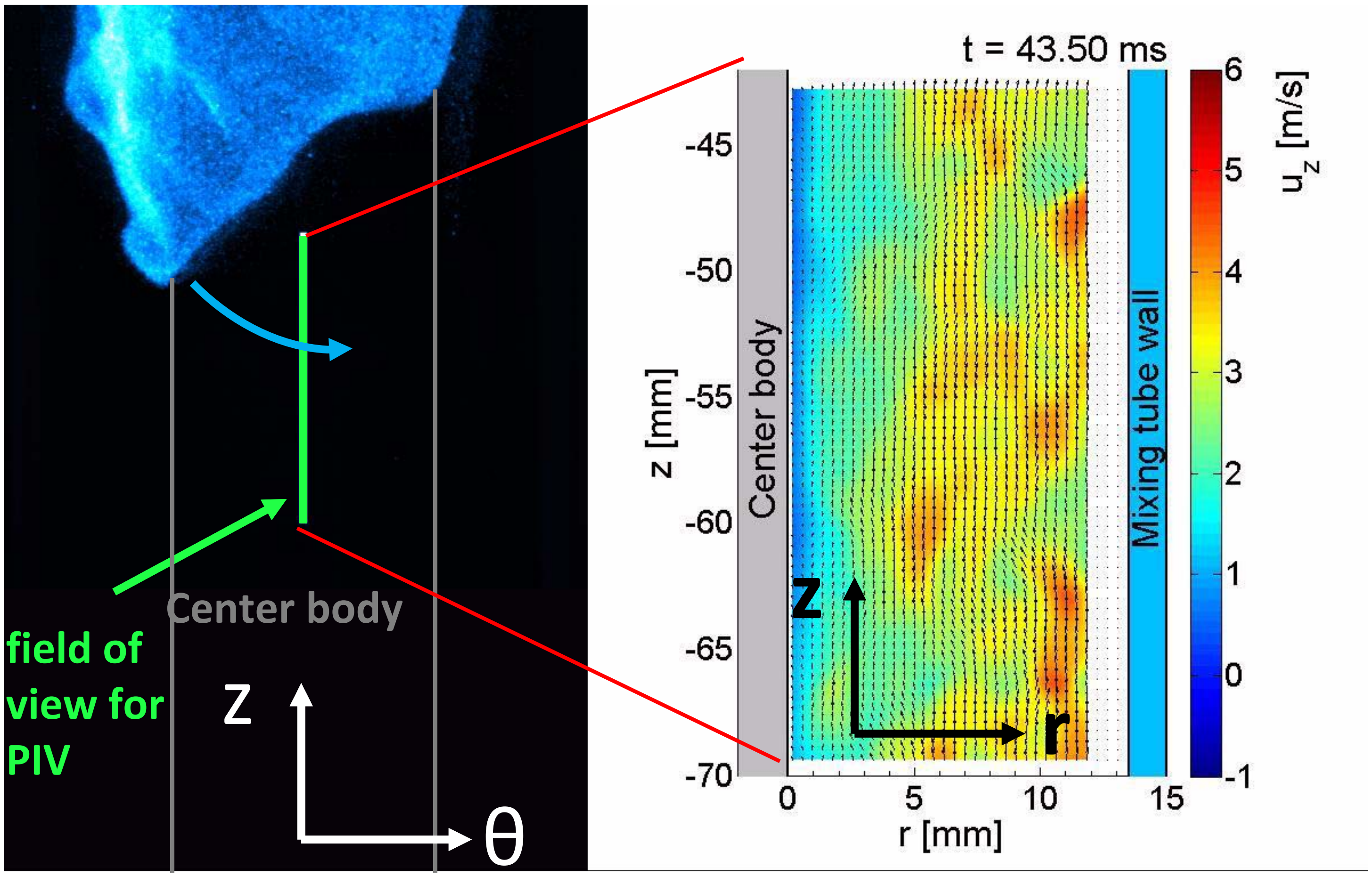
Field of view for velocity measurements



CH_4-air flame flashback

flame luminescence

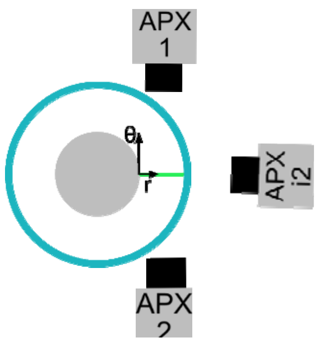
axial velocity

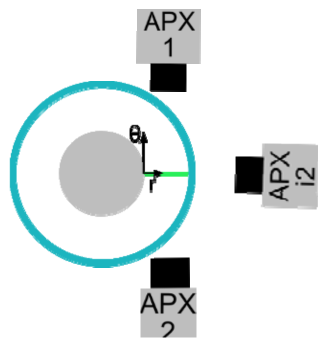


red line: flame front

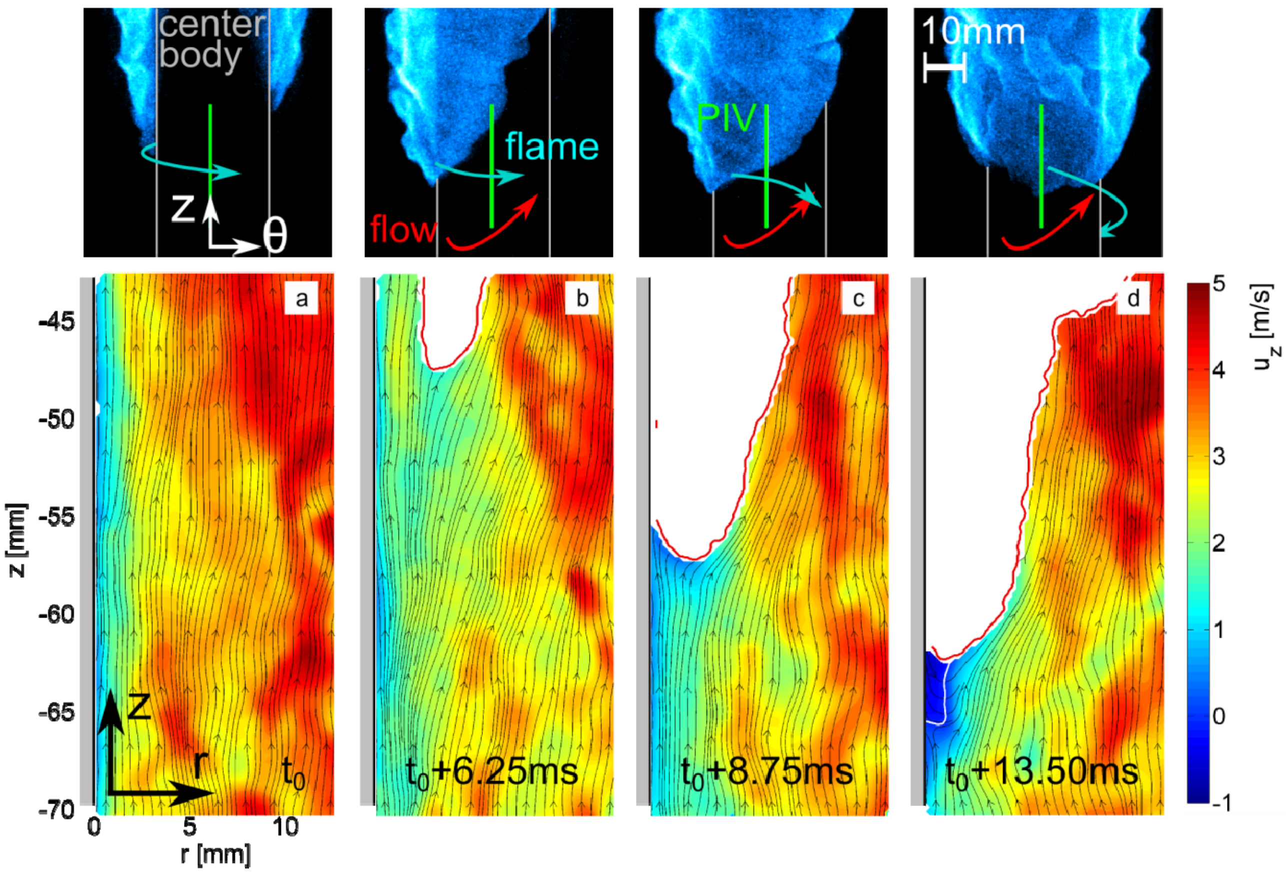
white line: isoline of 0 m/s axial velocity

field-of-view:





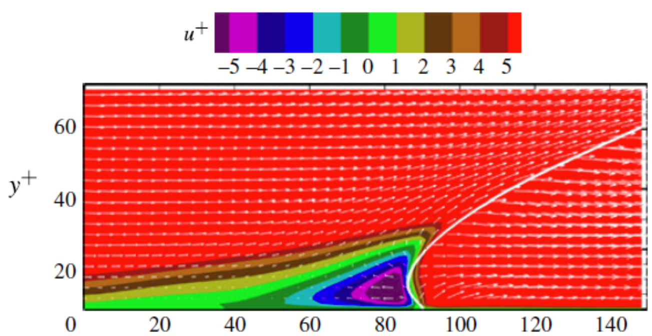
CH_4-air flame flashback



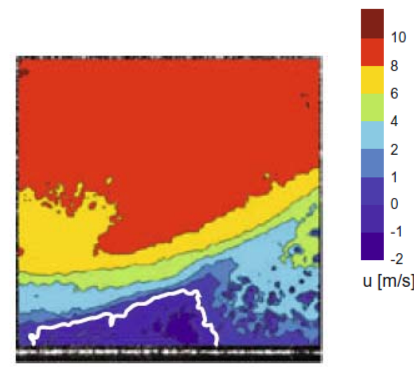
- Upstream flame propagation always associated with region of negative axial velocity upstream of flame
- Shown here as an example: $Re_h \approx 4,400$, $\varphi = 0.8$
- Simultaneous luminescence imaging from orthogonal view eliminates ambiguity in interpreting planar data

BL flashback: channel vs. swirling flow

- Channel flow



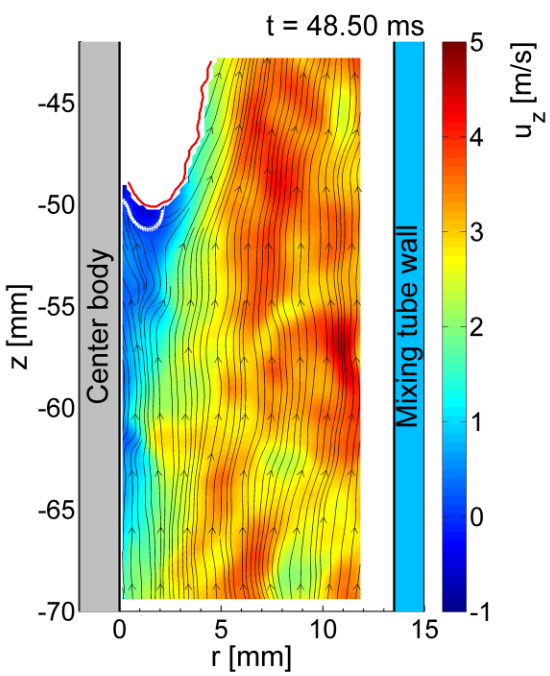
Gruber, A., Chen, J. H., Valiev, D., Law, C. K., *Journal of Fluid Mechanics*, Vol. 709, 2012.



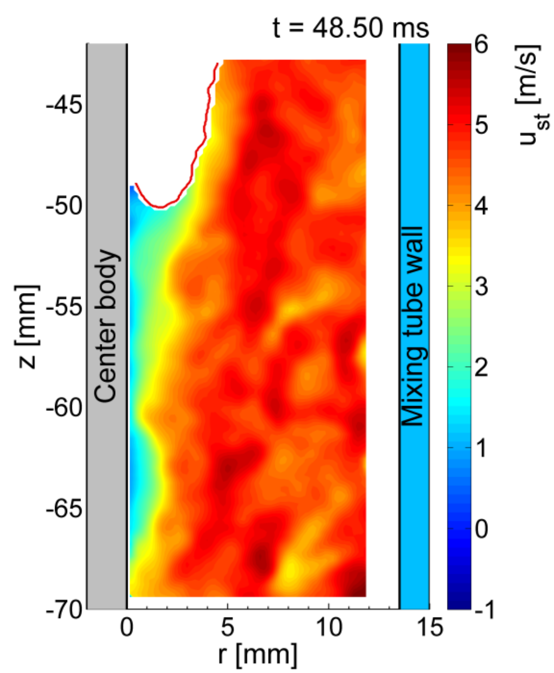
Eichler, C., Sattelmayer, T., *Experiments in Fluids*, Vol. 52, No. 2, 2011.

- Swirling flow

axial velocity

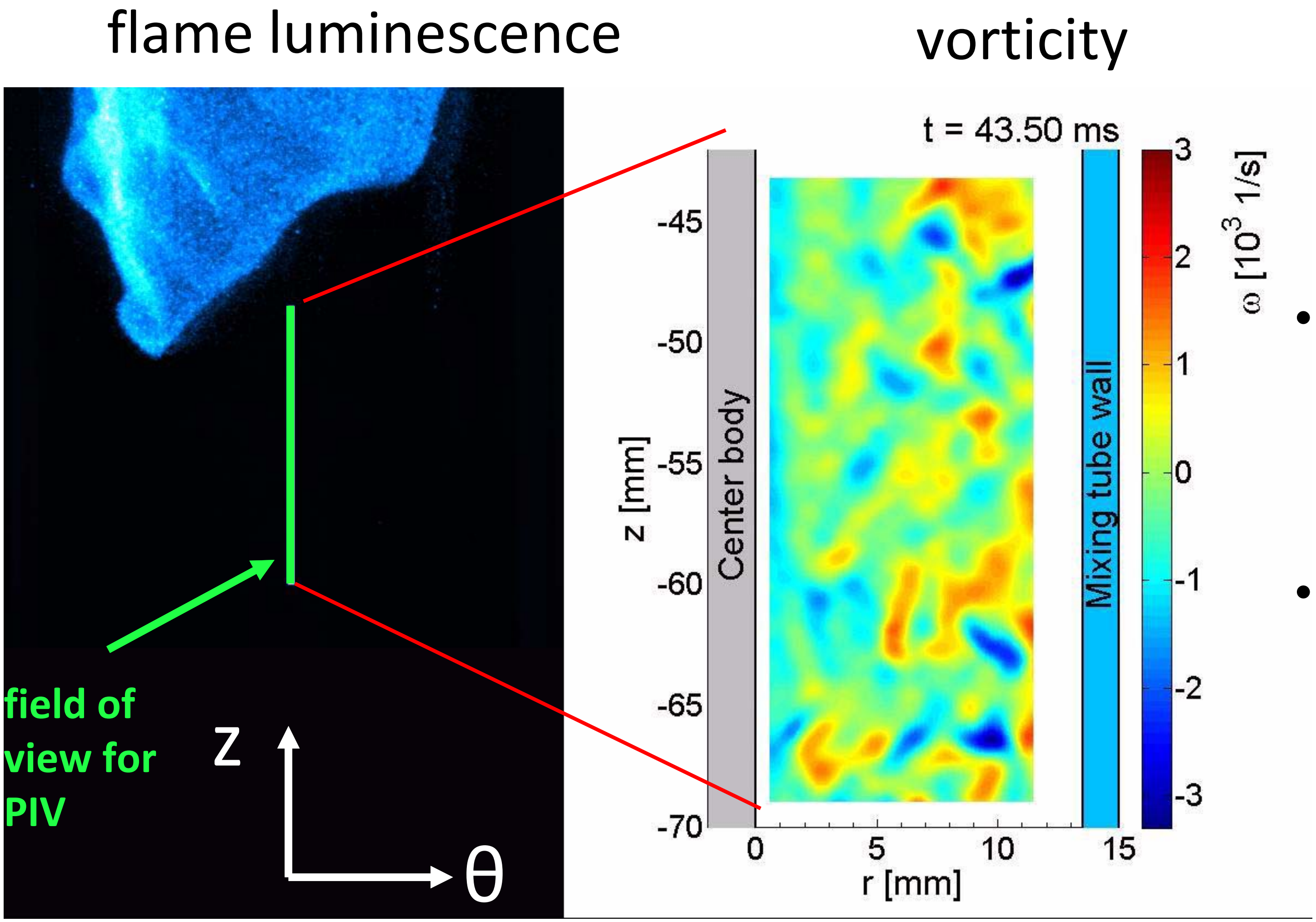


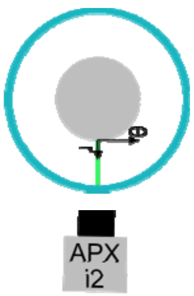
streamwise velocity

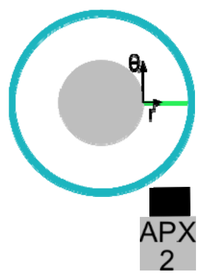


- Region of negative axial velocity (left)
- However, no reverse flow in undisturbed mean streamwise direction (right)

Vorticity field





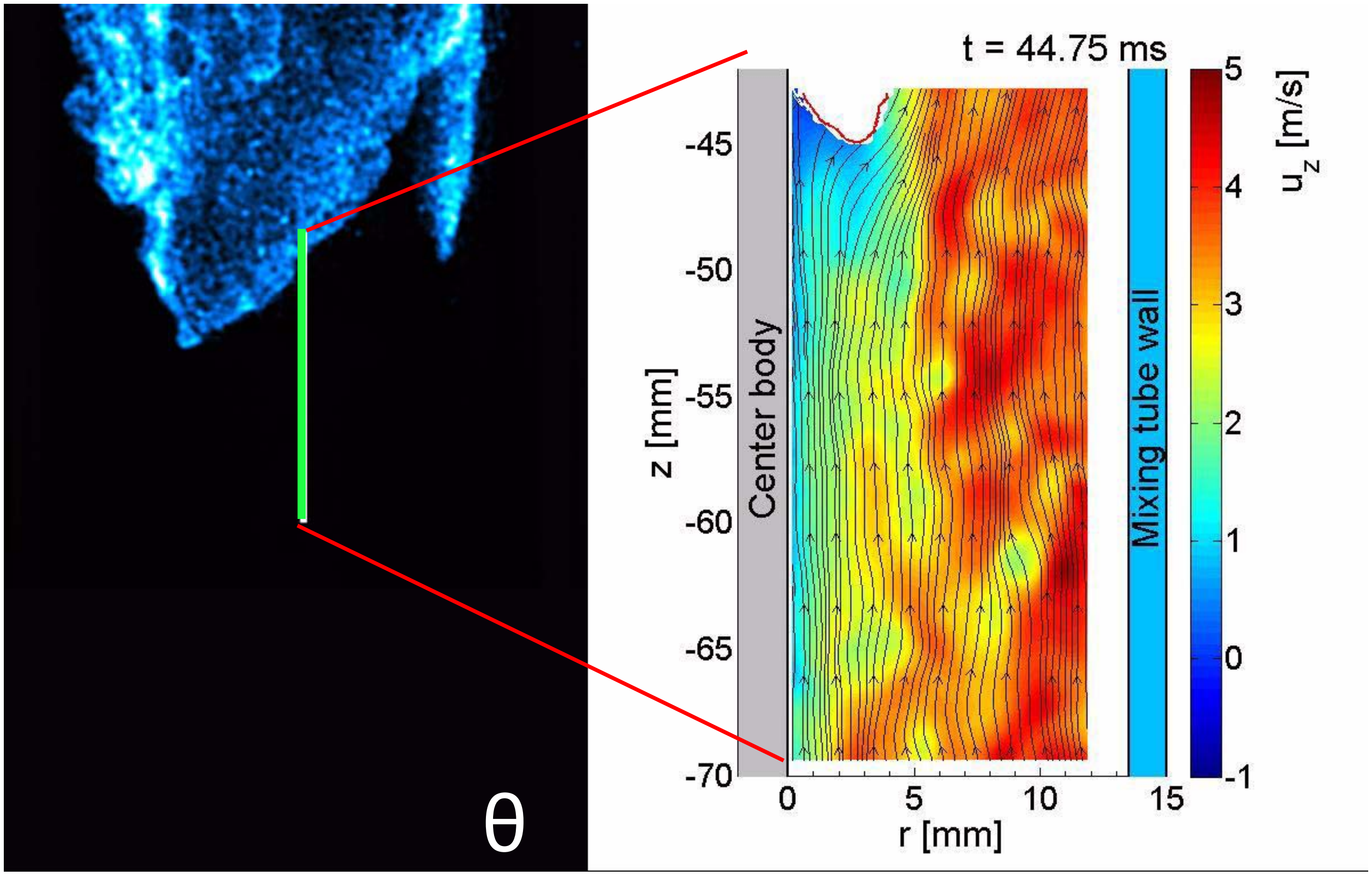


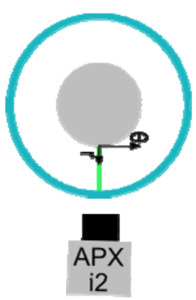
- Coherent motion of structures highlights the quality of the data
- Layer of negative vorticity along the center body wall as the flame tip enters the field of view

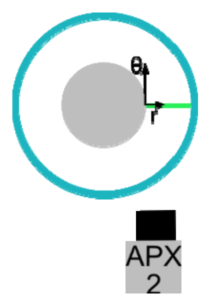
H_2/CH_4-air flame flashback (90% H_2 by vol.)

flame luminescence

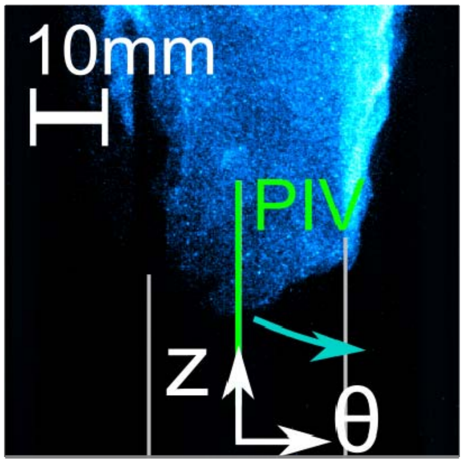
axial velocity

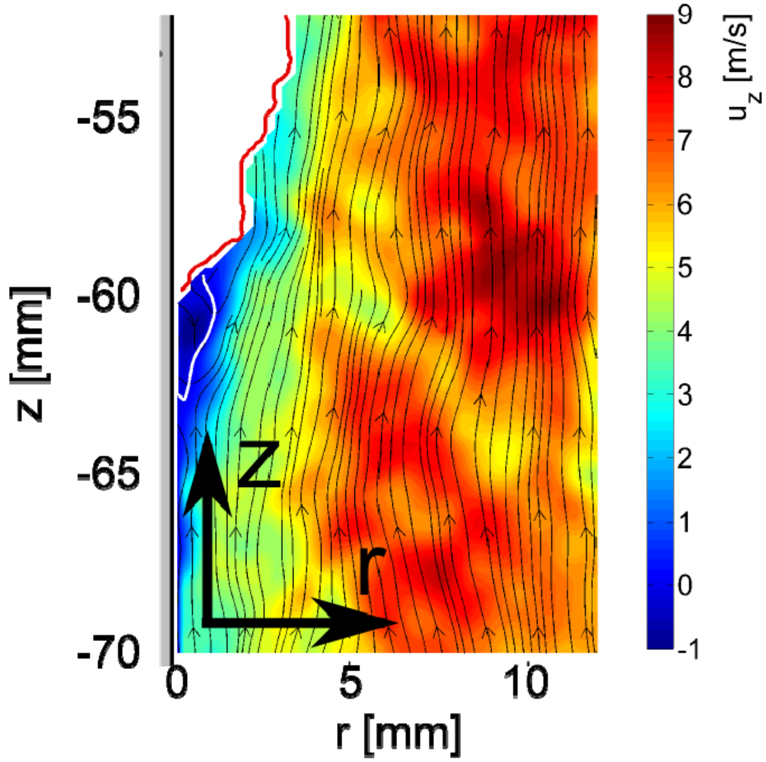






Effect of Reynolds number





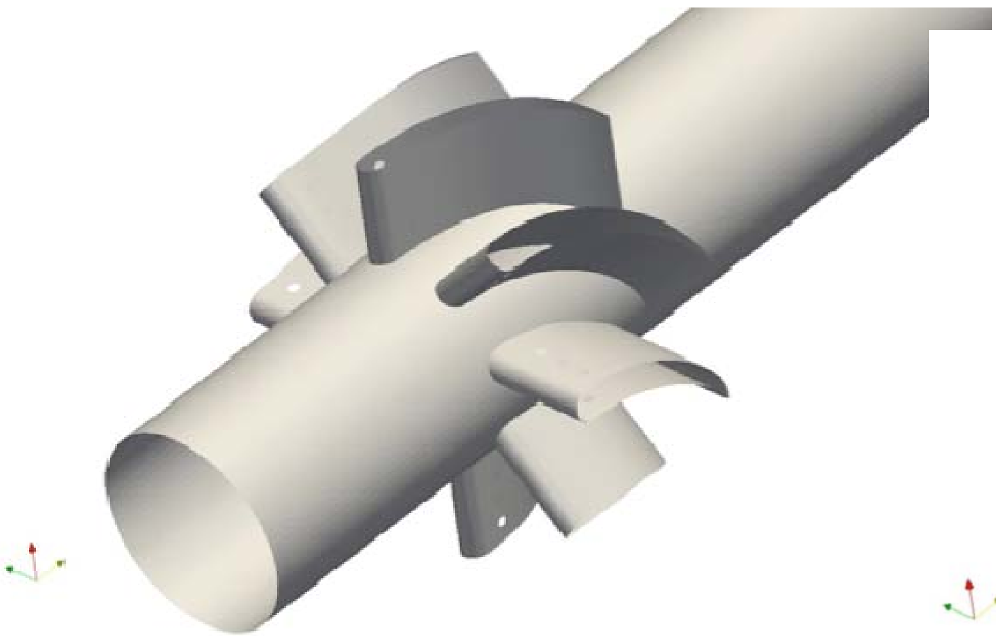
- Flashback of CH4-air flame at $Re_h \approx 9{,}200$ in comparison to $Re_h \approx 4{,}400$ case shown before
- Flame surface more wrinkled as expected, but characteristics of upstream flame propagation unaltered
- Suggests that a lot can be learned from lower Reynolds number cases

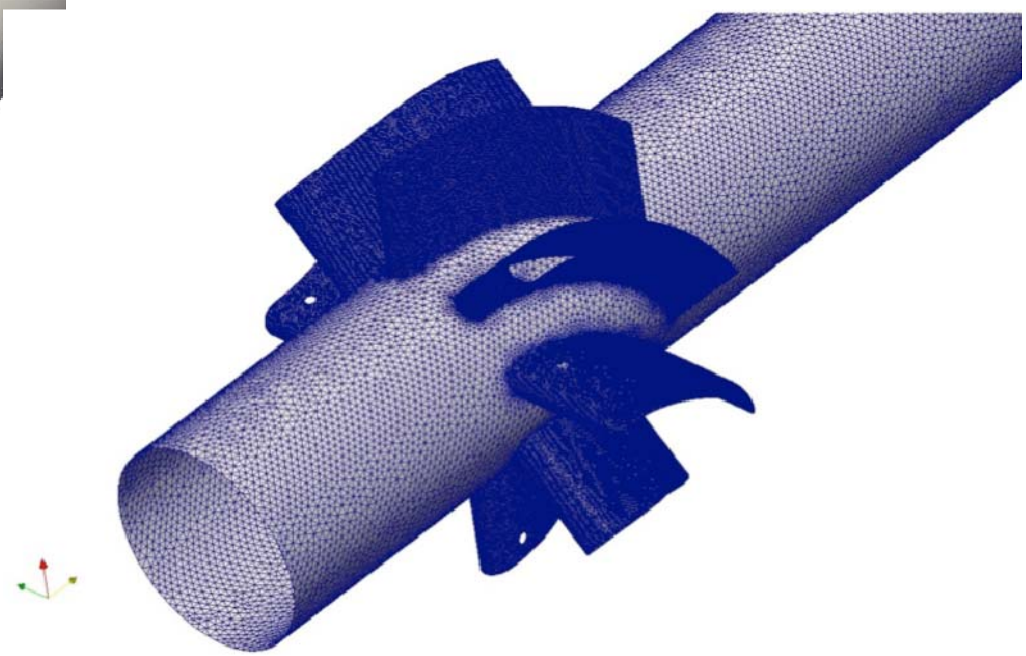
Large Eddy Simulation of Flashback

- Goal of LES two-fold
  - ➞ Understand current capabilities
  - ➞ Develop models in an open source framework for easy transfer to industry
- Flamelet-based modeling
  - ➞ Flow conditions considered fall in the flamelet regime
  - ➞ Progress-variable/enthalpy formulation
- OpenFOAM solvers for combustion
  - ➞ Open source CFD plaftorm
  - ➞ Adapted for LES and turbulent combustion

Large Eddy Simulation of UT Swirl Burner

- OpenFOAM based simulation
  - → Allows transfer to industry without additional legal issues
  - → Integration of models developed in this work
- CAD geometry from experimental group used directly
  - → Critical for transfer to industrial simulations



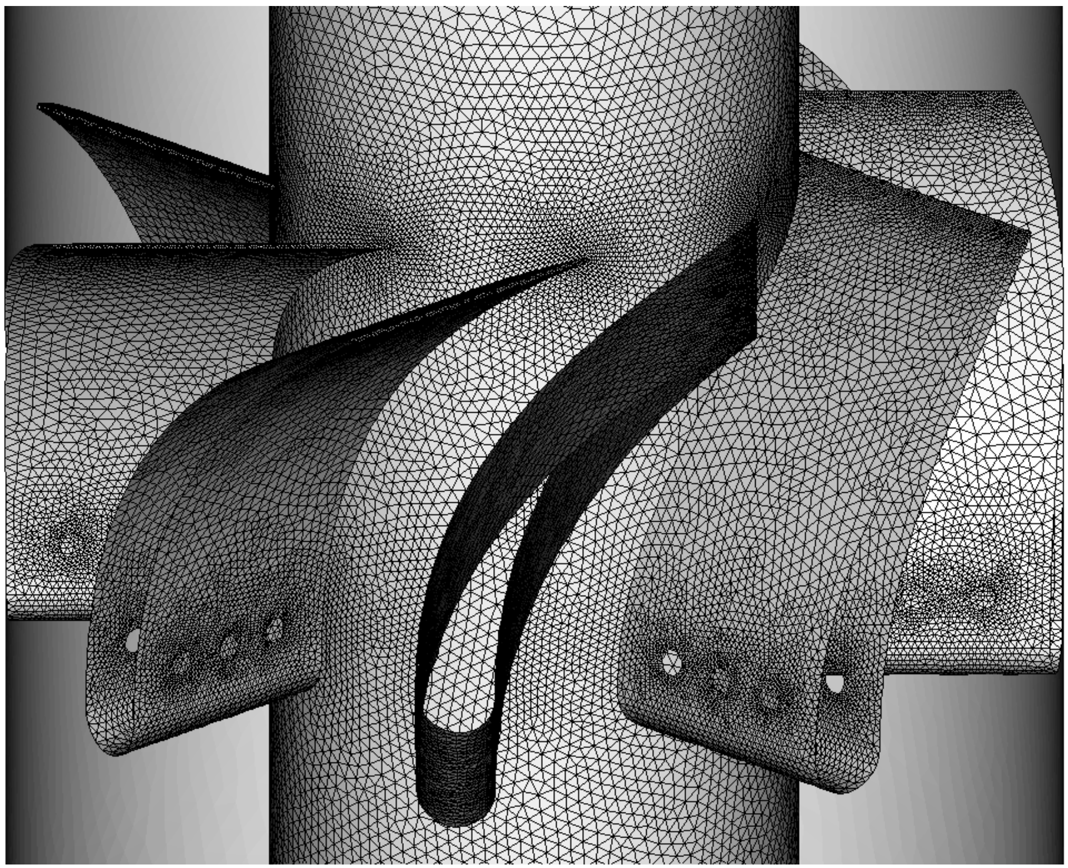


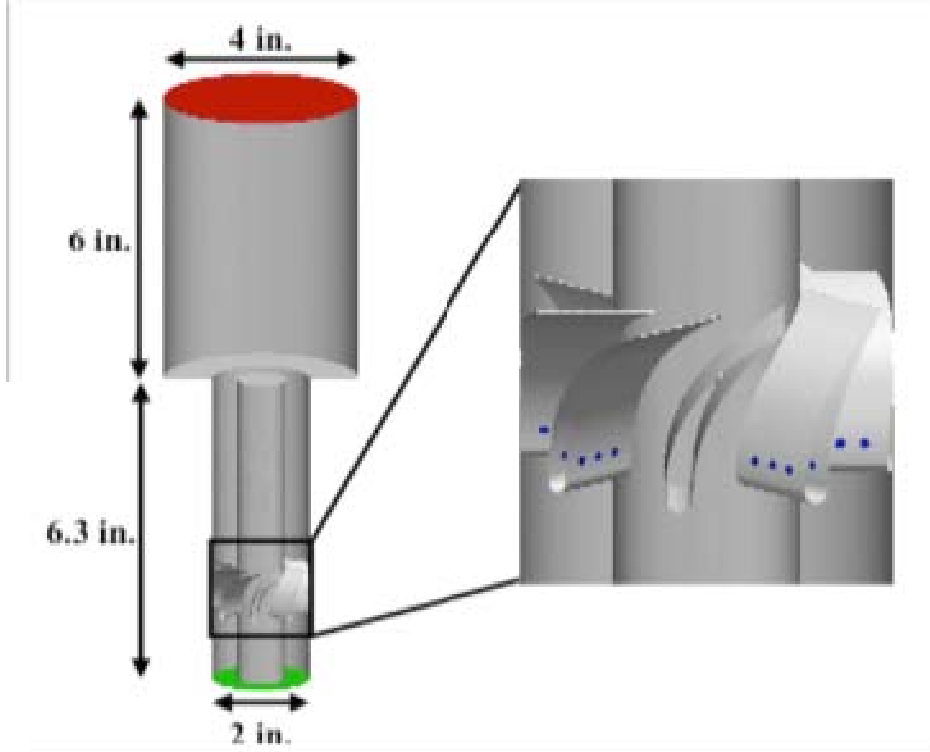
OpenFOAM for LES

- Base software not suitable for high-fidelity LES
  - → High numerical diffusion
  - → Lack of robust numerical algorithms for low-Mach number flows
- New OpenFOAM module for combustion developed
  - → Incorporates pressure-based low-Mach number solver
    - Robust for high density ratio flows
  - → Improved temporal accuracy
  - → Includes flamelet-type combustion models
    - PDF/quadrature approaches also implemented

Computational Domain

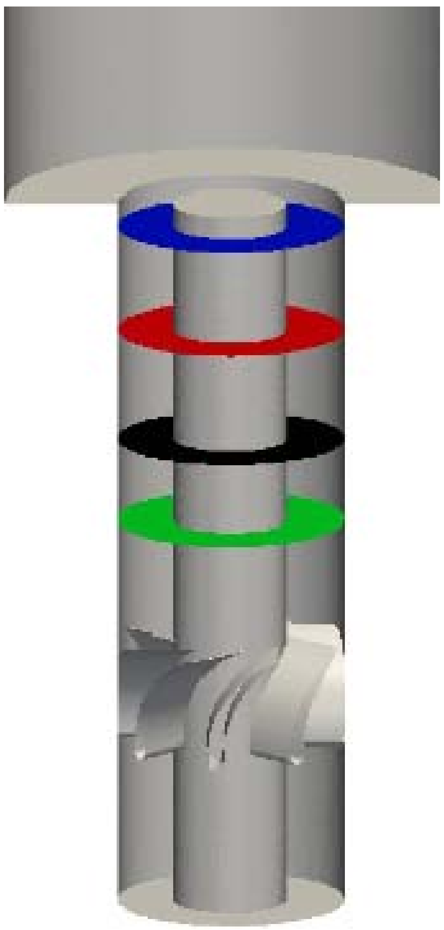
- Unstructured grid
  - ➞ Based on CAD file
  - ➞ Clustered grid

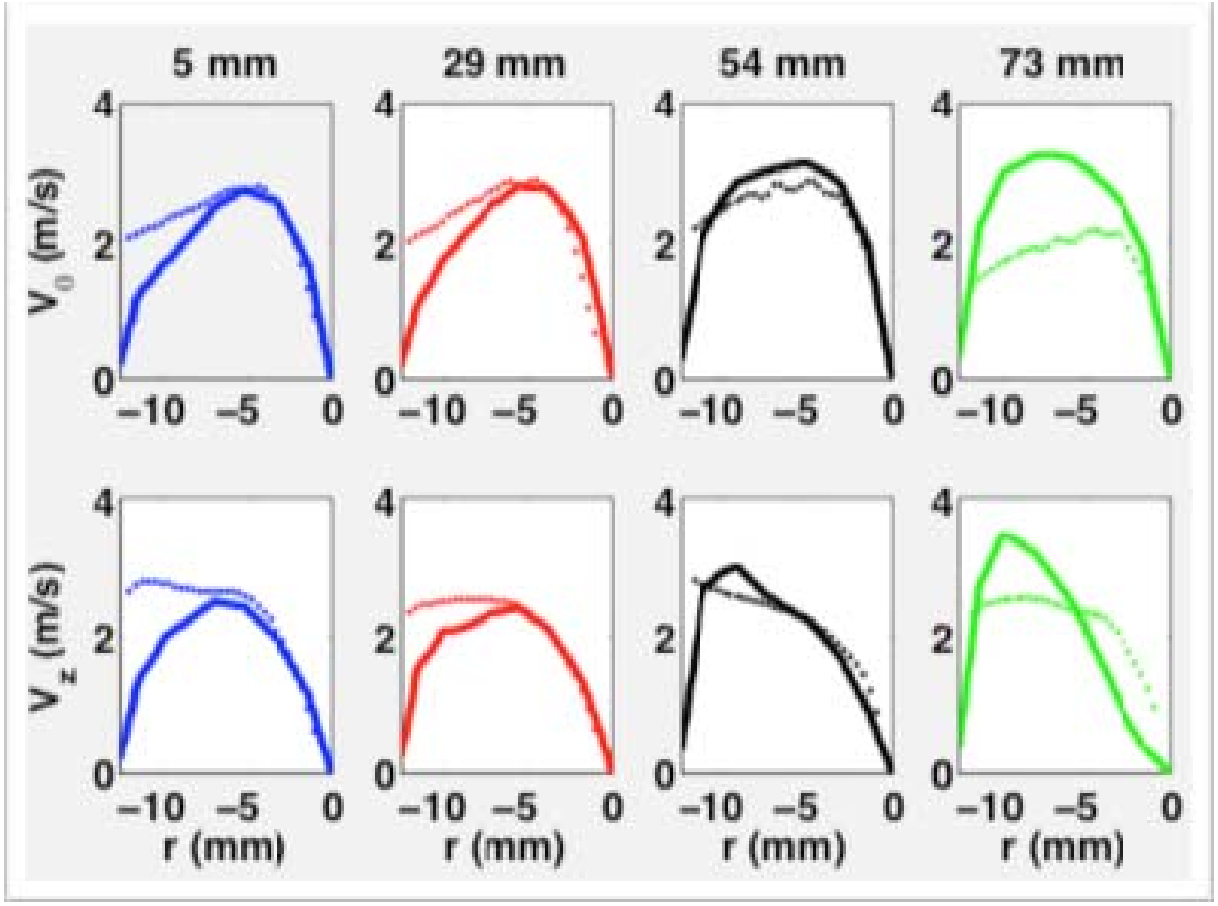




Fuel	CH_4	CH_4	CH_4	CH_4	H_2	H_2	H_2
Bulk velocity (m/s)	1.1	2.2	3.4	4.6	1.1	2.3	3.4
ϕ (stable flame)	0.6	0.6	0.6	0.6	0.15	0.15	0.15
ϕ (flashback)	0.67	0.64	0.77	0.80	0.22	0.20	0.21

Inert Flow Field Validation





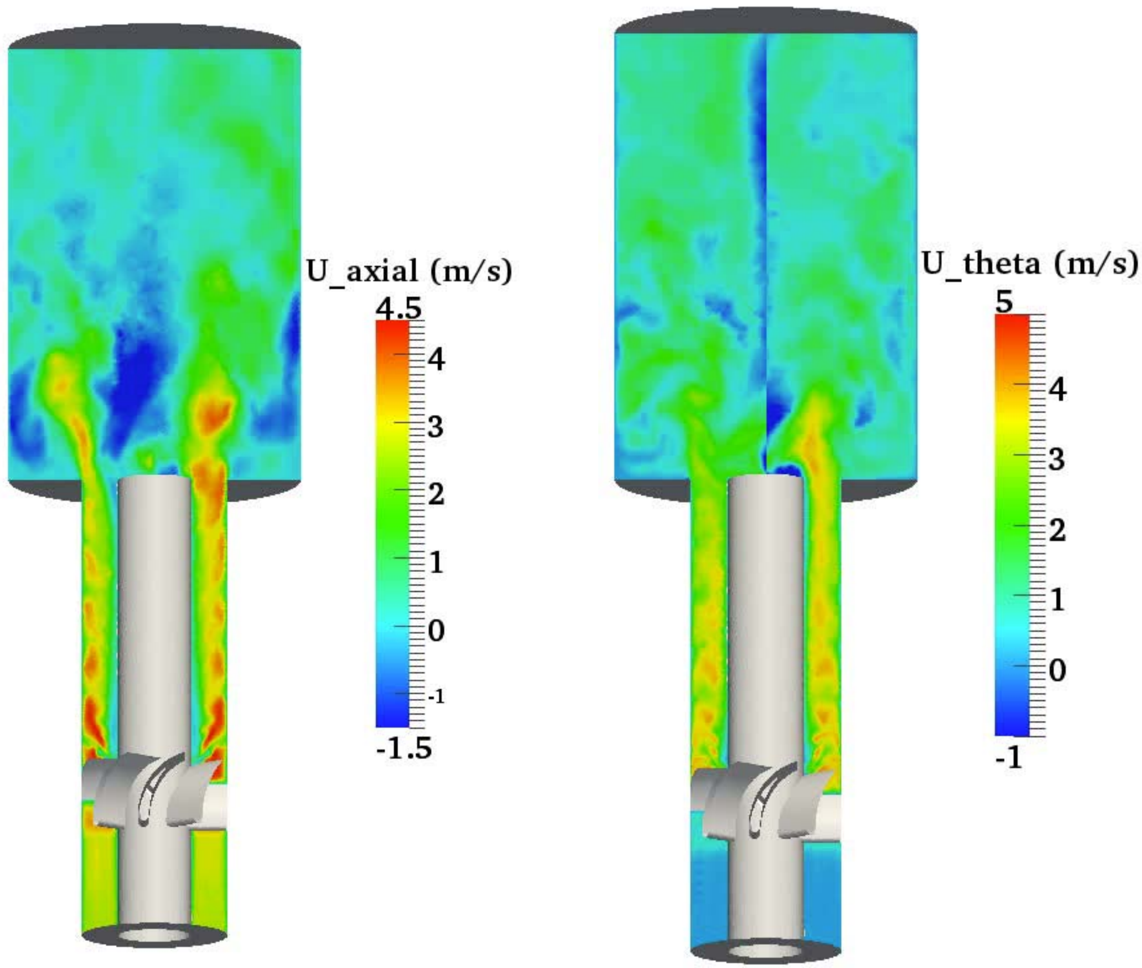
Mean velocity components for experimental results (points) and LES results (lines)

High-speed Velocity Streaks

- Streaks of high axial and azimuthal velocity forms in the mixing tube
- Flame flashes back in the low-velocity regime
- Turbulence breakdown affects streak alignment

Swirl Structure

- Mixing tube
  - → Swirl structure determined by vane angles
  - → Small differences due to turbulence development
    - Leads to misalignment with experimental data

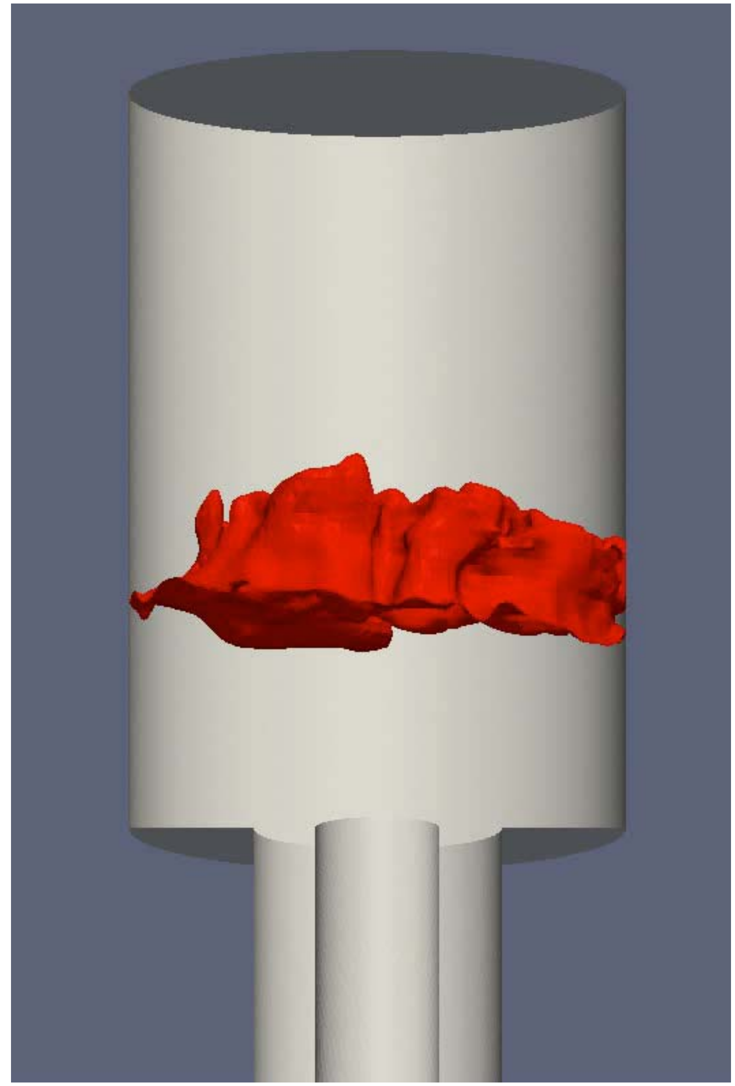


Flame Description

- Flamelet-based model
  - → Flame described using progress variable
  - → Only valid for constant equivalence-ratio systems
- Flame flashback induced using step-change in equivalence ratio
  - → Implies a change in local fuel/air composition
  - → Requires a mixture-fraction based description
- Mixture-fraction/Progress variable approach
  - → Based on an ensemble of premixed laminar flamelets
  - → Neglects interaction between different flamelets
    - – Weak stratification assumption

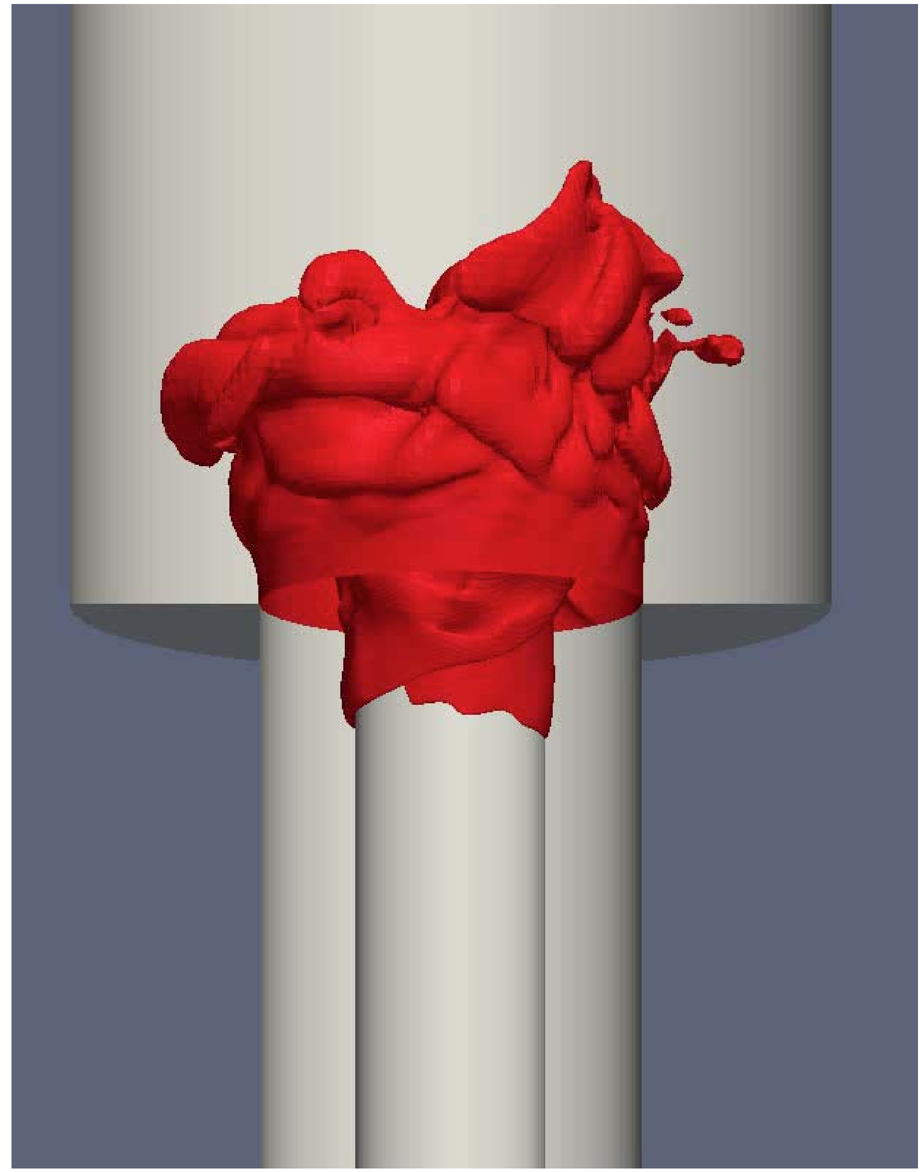
Achieving Stable Anchored Flame

- Chosen equivalence ratio used to stabilize the flame
- Flame surface initialized as a flat flame at arbitrary height inside chamber
  - → Allowed to stabilize and reach statistical stationarity
  - → Flame found to travel close to premixing tube
  - → Frequent entry into premixing tube



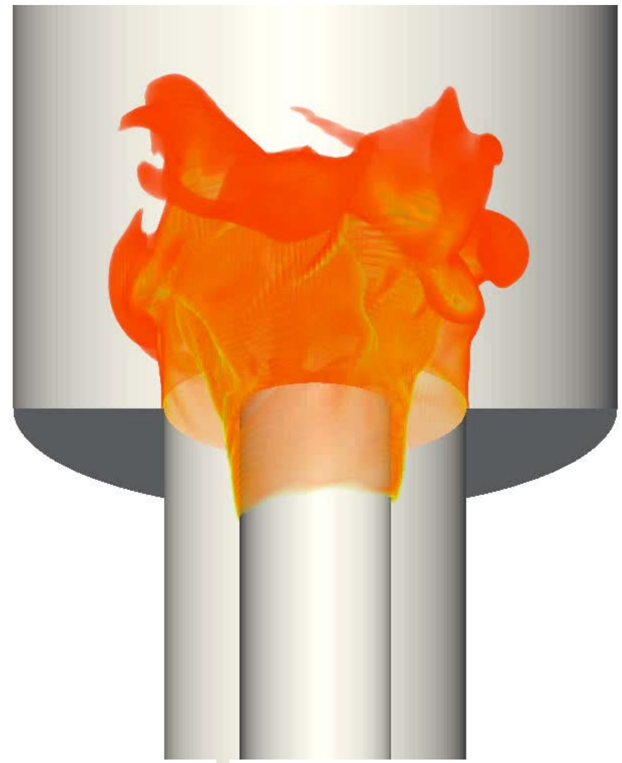
Numerical Flashback

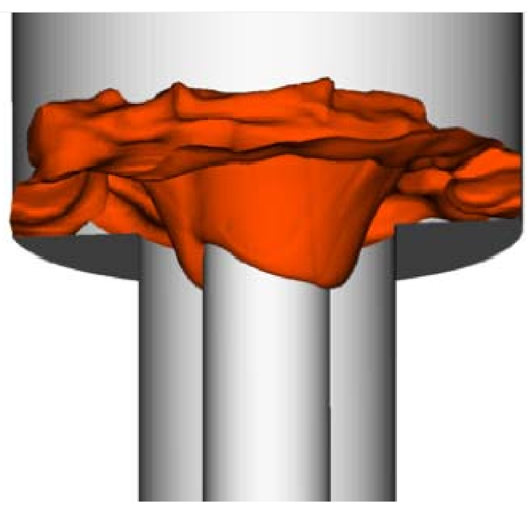
- Step-change in equivalence ratio at the inlet
  - → Finite time to reach the flame front
  - → Shortest time through high-velocity streaks
  - → Imposes a fuel gradient in the flashback region

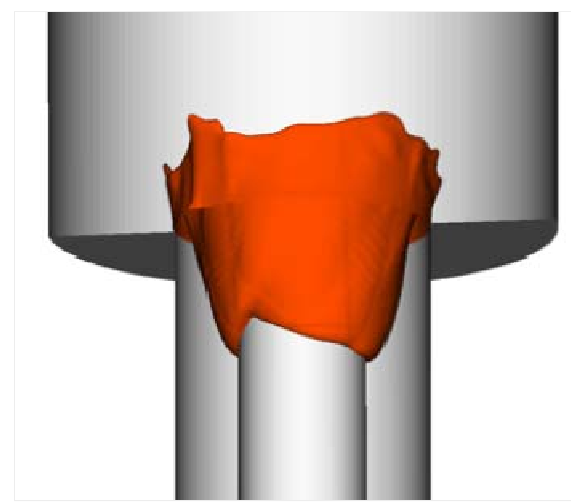


Flame Behavior in Mixing Tube

- Flame propagation along inner wall
- Flame speed trend with Re consistent with experiments
  - → Higher Re leads to higher flashback speeds
- Increased laminarization
  - → Partly due to filter width effects

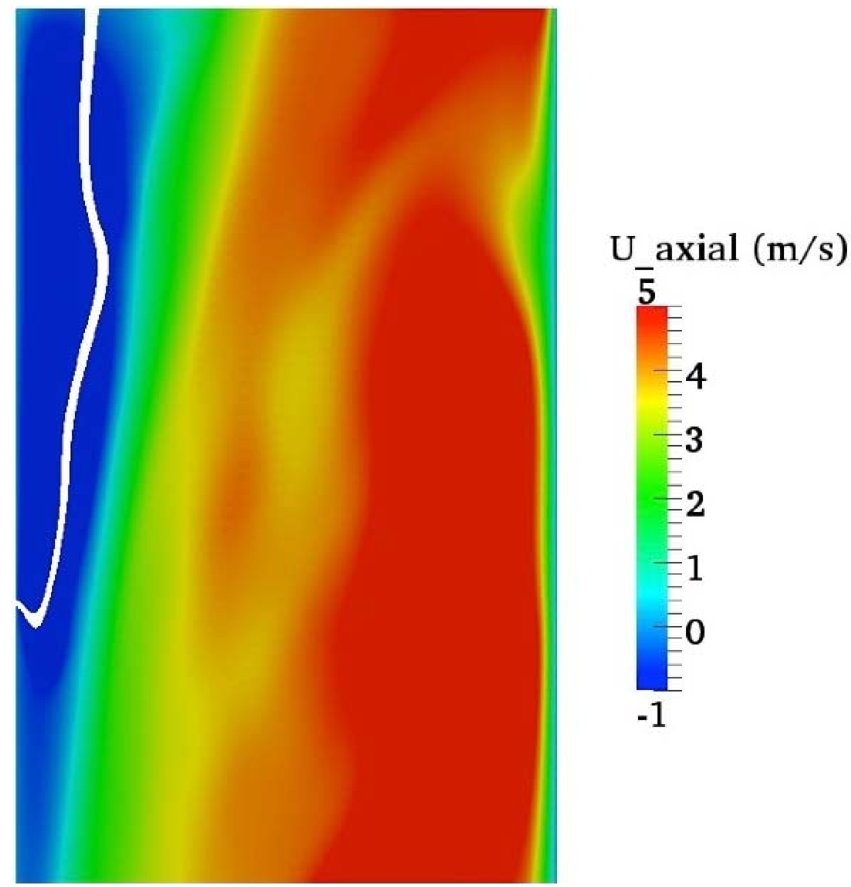






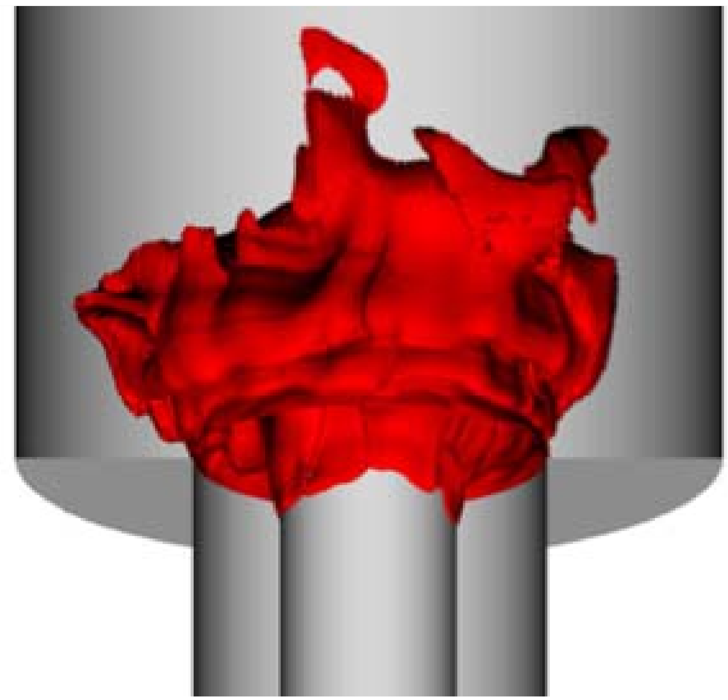
Flashback Physics from Simulations

- Weak reverse flow ahead of flame
  - → But larger negative velocity behind flame compared to experiments
- Reverse flow not essential for flashback
  - → Flashback speed is roughly equal to that in experiments
  - → Predicted for different fuel compositions and Re



Hydrogen-enhanced Flames

- Higher hydrogen content increases flame wrinkling
  - → Larger density ratios
- Flame front radially distributed compared to experiments
  - → Possibly from inaccurate heat loss model
- Reverse flow is still not critical in the simulations
  - → Discrepancy noticed in other channel flashback simulations as well



Final Steps

- Direct quantitative comparison of simulations and experiments
  - → Preliminary analysis completed; Students working on final set of high-resolution simulations
- High pressure data
  - → Part of second project
  - → Rig built and tested; Initial runs complete
  - → Simulations are being carried out blind for comparisons

Conclusions

- Boundary layer flashback exhibits complex dynamics
  - ➞ Flame propagation mode depends on fuel composition
  - ➞ Strong influence of swirl flow momentum
  - ➞ Propagation along weaker boundary layer
    - Inner wall boundary layer in the UT swirler configuration
- Open source LES solver developed and tested for complex reacting flows
  - ➞ Ready to be transferred to industry
  - ➞ Collaboration with Siemens Inc. in progress
- LES predicts trends but not quantitatively accurate
  - ➞ Lack of reverse flow could be tied to low-Mach number assumptions

Outstanding Issues

- What is the role of near-wall flow on flame propagation
  - Is reversed flow important?
  - How does anisotropy at the wall affect propagation?
- Effect of pressure
  - Are pressure gradients near wall important for accelerating flame propagation?
- What is LES of flashback?
  - LES provides an unsteady transient simulation
  - However, is this directly comparable to experiments?
  - What does a single realization of experiment and LES mean?