Low-Swirl Injectors for High Hydrogen Fuel Gas Turbines

Robert K. Cheng

Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Research supported by NETL - Fossil Energy, US Dept. of Energy

Presentation at UTSR Workshop - Oct. 26, 2011

BERKELEY LAB
Lawrence Berkeley National Laboratory

Participants and Collaborators

- LBNL – Environmental Energy Technology Div.
  - Robert Cheng, David Littlejohn, Peter Therkelsen, Ken Smith, & Sy Ali
- United Tech. Research Center – Pratt & Whitney Power Systems
  - Dustin Davis, Justin Locke, Catalin Fotache & Richard Tuthill
- Florida Turbine Technologies
  - Russell Jones & Joe Brostmeyer
- LBNL – Computational Research Div.
  - John Bell & Marc Day
- Siemens Energy Inc.
  - Scott Martin & Enrique Portillo Bilbao
- University of California, Irvine
  - Vince, McDonnell, David Beerer & Adrian A. Narvaez

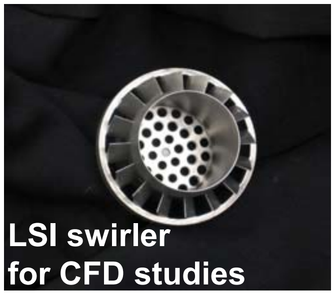
Challenges for Combustion Turbines in IGCC Plant with Carbon Capture and Storage

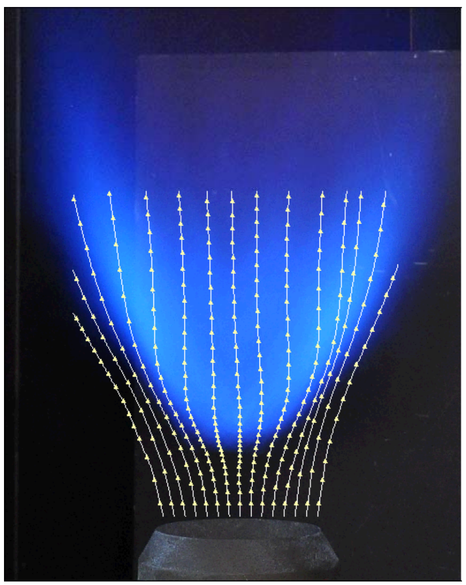
- Desired fuel-flexibility
  - Use natural gas for startup and backup fuel
  - Burn syngases from coal gasifier (CO, H_2, CO_2 and other inert) during transition to base-load to minimize flaring of syngases to the atmosphere
  - Operate at base-load on high hydrogen content (HHC) fuels of 80% to 90% H_2 produced by water-shift reaction of syngases
- Emissions, operability, and cost tradeoffs
  - No one-size-fits-all solution

Project Overview

- Objective
  - Develop a cost-effective DLN combustion technology for the gas turbines in Near-Zero Emissions Clean Coal IGCC Power plants that burn coal-derived syngases and HHC fuels
- Main Tasks
  - Establish scaling rules and engineering guidelines for syngases and hydrogen low-swirl injectors (LSI)
  - **Modify LSI to operate effectively and safely with syngases and hydrogen fuels**
  - **Transfer knowledge to OEMs for scale-up and adaptation to HHF gas turbines**
  - Assist OEMs to develop fully-functional LSI combustors for the HHF gas turbines in IGCC
  - Participate in demonstration of LSI in utility-size gas turbines that meet the cost and performance targets of FE’s Advanced Turbine Program

Fuel-Flexible Low-Swirl Injector Development Status





- Demonstrated fuel-flexible LSI operation at STP
- Modified nozzle exit profile to mitigating combustion dynamics
- Addressed issues specific to H_2 flame behavior
- Developed and tested a sub-scale fuel-flexible LSI at gas turbine relevant conditions

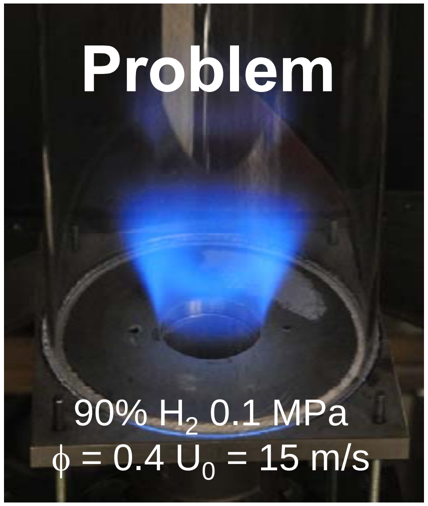
Conceptual Design Study of LSI for 3-fuel Gas Turbine

- Subcontract to United Technology Research Center and Pratt & Whitney Power Systems (UTRC/PWPS)
  - Gas turbine manufacturer participation to address Technology Readiness Level (TRL)
- Objectives
  - Conceptual architecture of a 3-fuel LSI system and operation models
  - Design and fabricate a fully functional sub-scale LSI for natural gas and hydrogen-rich fuel blend
  - Verify natural gas and HHF operation at realistic gas turbine conditions

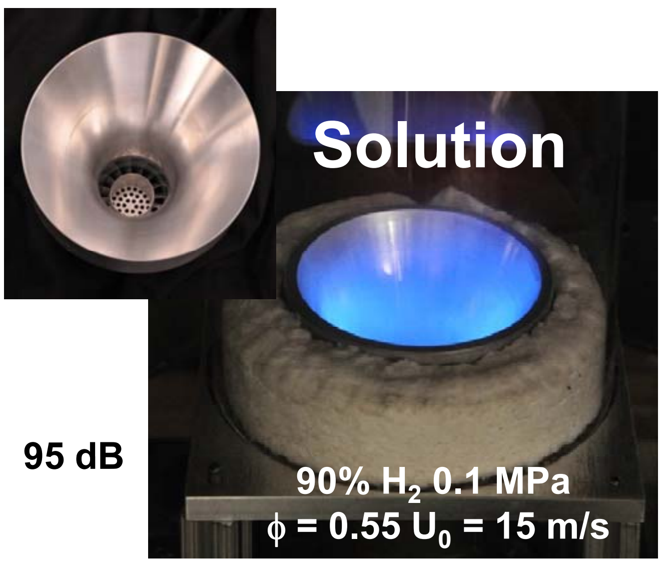
BERKELEY LAB

Modified LSI Nozzle Exit Profile to Address H_2 Flame Issues

160 dB

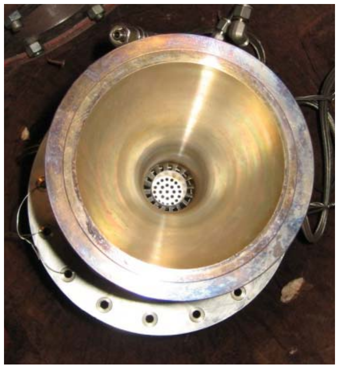


95 dB



- H_2 burn in the outer shear layer resulting in attached flames
  - Alters flame stabilization mechanism and incites flame instability
- Straight edge divergent quarl mitigates flame instability but does not solve flame attachment problem
- Smooth wall flared nozzle mitigates shear layer burning, extends range of operation, and reduces flame acoustics

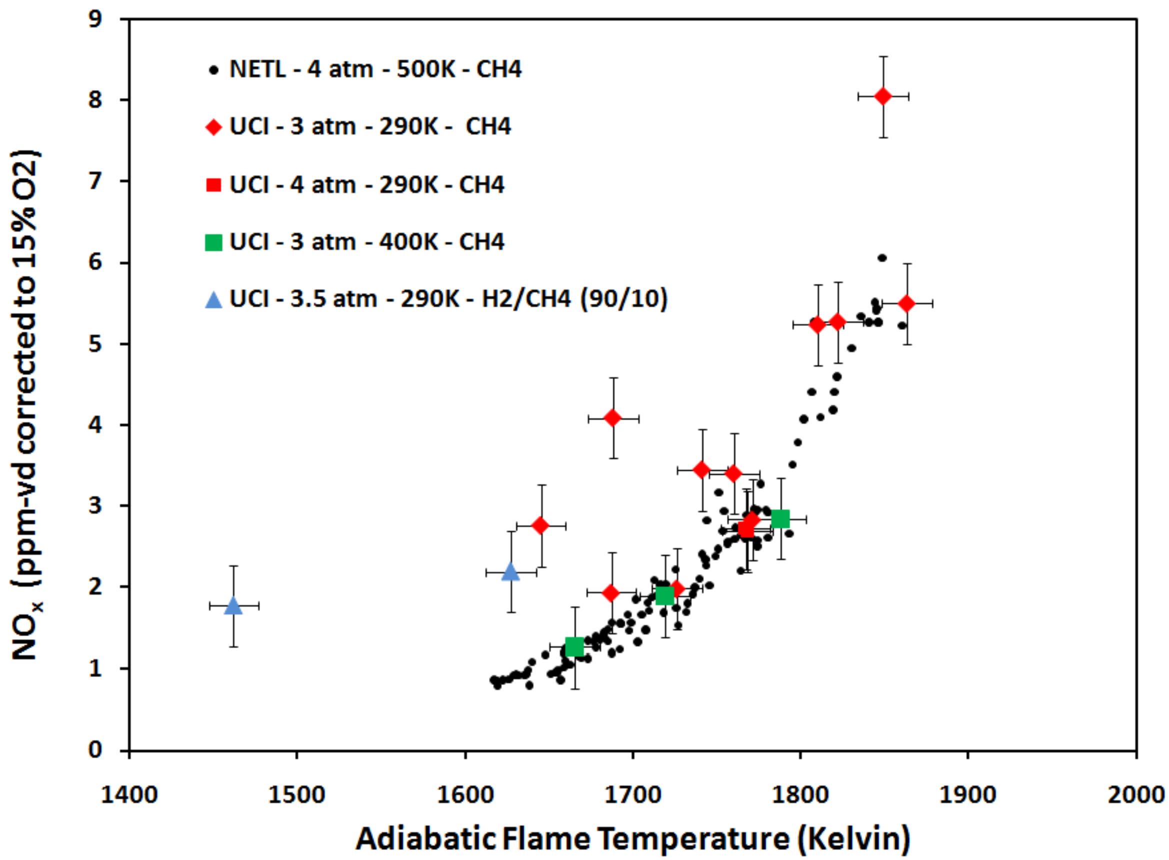
Verification of Flared Nozzle Operability at Simulated Gas Turbine Conditions



- LSI with flared nozzle fabricated for U.C. Irvine's down fired high pressure facility
  - 3.8 cm I.D. with benchmark swirler design (16 thickened vanes, 37^o blade angle)
  - Upstream fuel spoke injectors
- Tested with natural gas and HHC fuel of 90% H_2 10% CH_4
  - $20 < U_0 < 30$ m/s, $3 < P > 6$ Mpa, $290 < T < 600$K
  - NO_x, flashback and blowoff investigated
  - IGTI paper planned

Despite Differences in Swirler Configuration, Premixer, and Nozzle Exit Profile, NO_x Emissions at UCI Comparable to Previous NETL Results

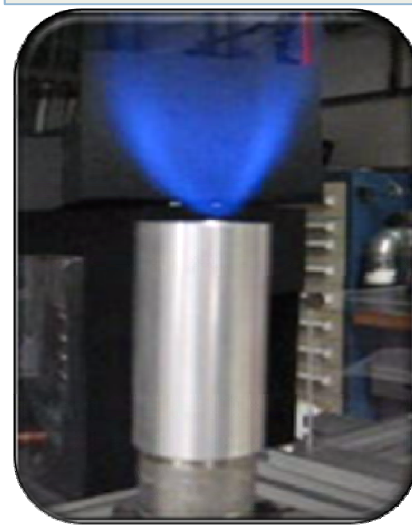
- H_2 flames have slightly higher No_x at lower T_{ad}
  - Vertical error bars show uncertainty of Horiba PG250
  - Horizontal error bars show uncertainty in equivalence ratio (+/- 0.02)



Sub-scale LSI Prototype Development

- **Close LBNL/UTC collaboration critical**

Rapid Screening at LBNL



Conceptual Design

Metal Hardware
- Fuel circuits
- UTR proprietary mixer
- Flares nozzle
- Swirler

LBNL Approval

Refined Concept

Rapid Prototype Resin Solid Models

CFD Design Tools

Results from Sub-Scale 3-Fuel LSI Prototype

- Tested with natural gas and diluted hydrogen at gas turbine relevant conditions
- LSI demonstrated stable operation (ease of light-off, loading, and very low dynamics) at all test points
- All NO_x emissions well below 10 ppm
  - Low single digit NO_x from natural gas matches Leonard and Seigmaier curve

Conclusions of UTRC Studies

- Verified multi-fuel LSI concept for gas turbine operation
- Found new operating mode for LSI
- Need some improvement for H_2 operation
- Design can be further simplified for scale-up

Florida Turbine Technologies Developing High Efficiency MW-size Gas Turbine with LSI

- Objective
  - Design a combustor around the LSI to enable high efficiency (approaching 60% in a combined cycle system) with ultra-low emissions
- Requirements
  - Single digit NO_x
  - Low combustor pressure loss
- Status
  - Initial system design complete
  - Detailed LSI combustor layout complete
  - Laboratory evaluation of LSI complete

Basic Research Supporting Technology Development

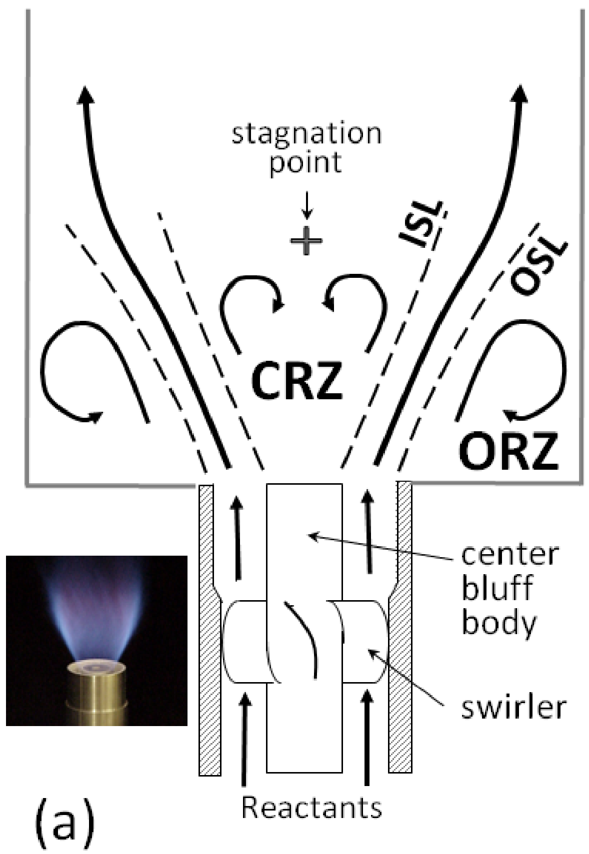
- LSI self-excited flame instabilities (collaboration with Siemens and UTRC)
  - Obtain basic understanding of combustion oscillation processes in gas turbines
- Turbulent displacement flame speed at gas turbine relevant conditions (collaboration with UC Irvine)
  - Investigate basic properties of premixed turbulent flames relevant to predicting flashback
- Symbiotic experimental/numerical studies of thermal/diffusive effects in turbulent lean HHC flames (collaboration with LBNL Computation Research Division)
  - Study basic turbulent flame structures to help develop model

LSI Flame Instability Mechanism

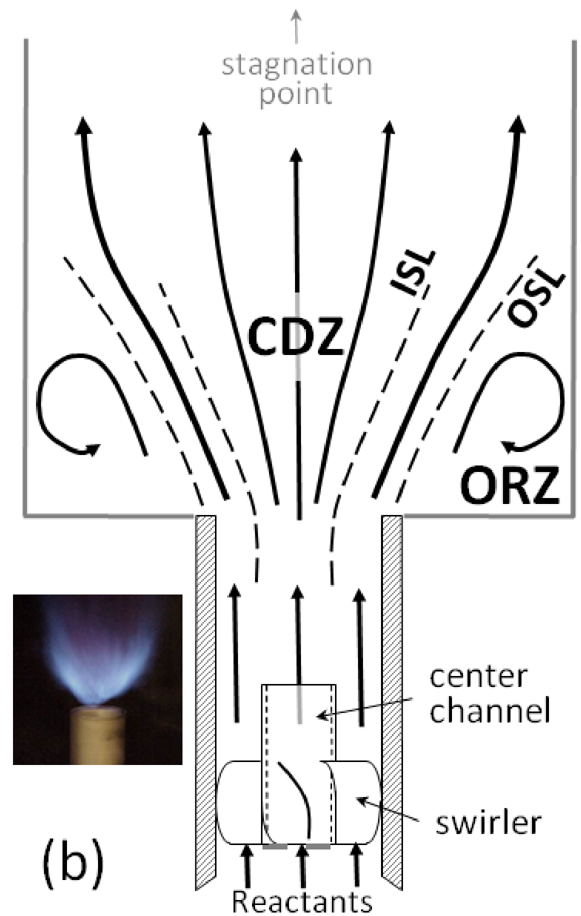
- Self-excited thermoacoustically unstable LSI flames
  - CH_4 and 90% H_2/10% CH_4 flames at 12 < U_0 < 18 m/s in model combustion chambers at standard conditions
  - Cylindrical chamber with sudden expansion dump plane without exit restriction
    - Facsimile of SimVal combustor at NETL
- Experimental methodologies (LBNL)
  - Acoustic pressure spectra
  - Coherent flame motion detection by laser beam deflection
  - Phase resolved particle image velocimetry
- Analysis of instability mechanism by a General Instability Model (Siemens)
- High speed imaging and analysis of unstable heat release (UTRC)

High Swirl vs. Low Swirl

High swirl injector uses a central recirculation zone (CRZ) to stabilize flames.



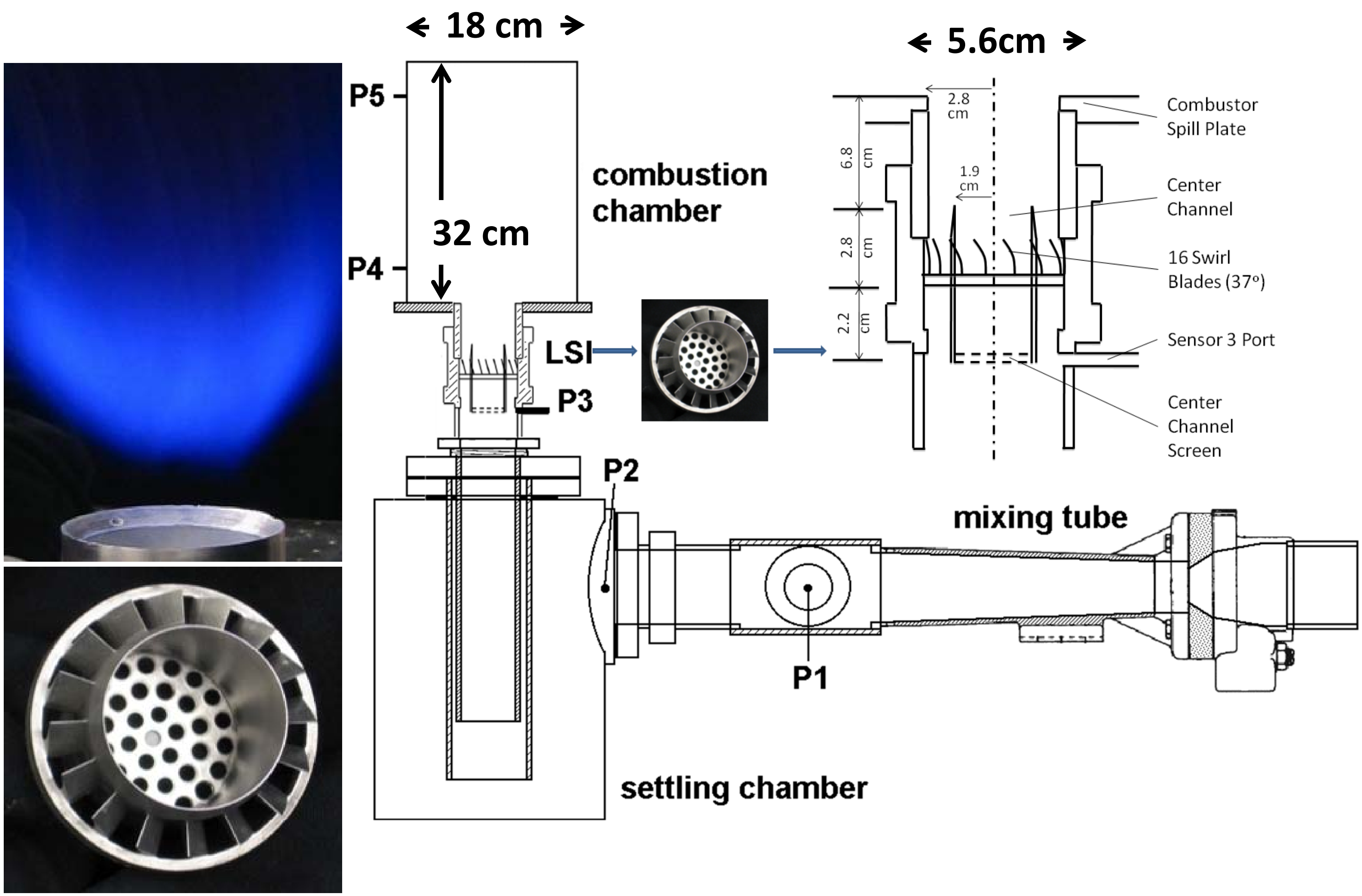
High Swirl



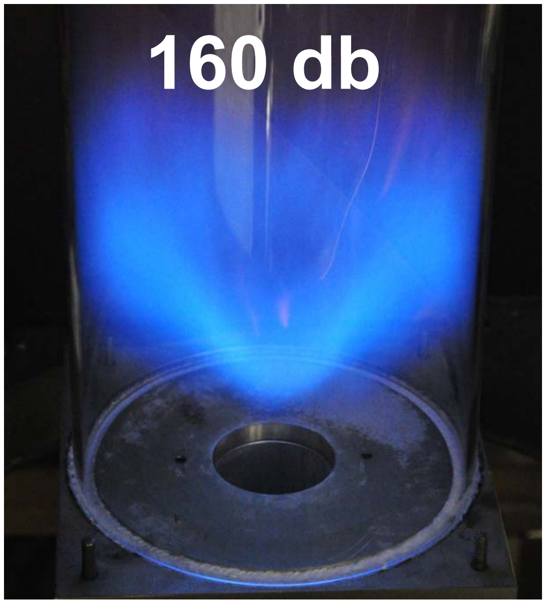
Low Swirl

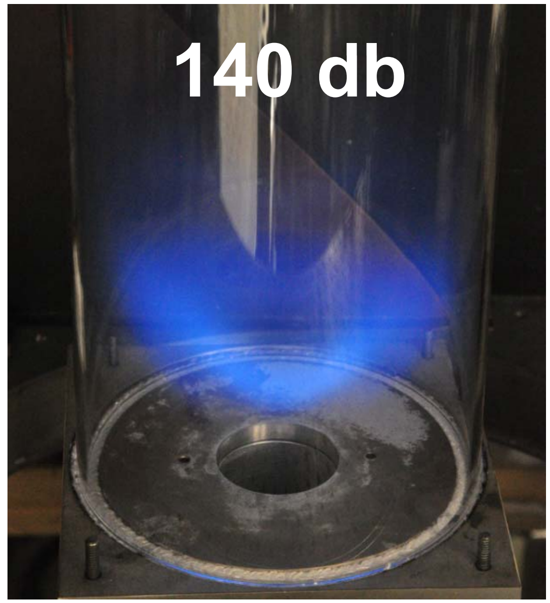
Low swirl injector stabilizes flames at the central divergence zone (CDZ)

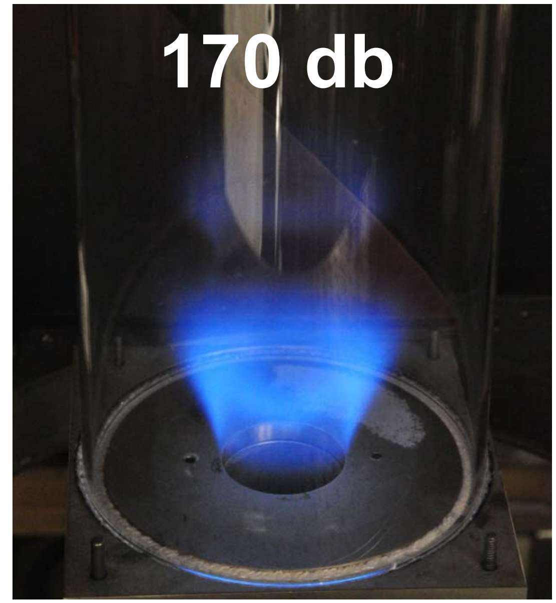
Experimental System



Enclosure and Fuel Effects on LSI Flames







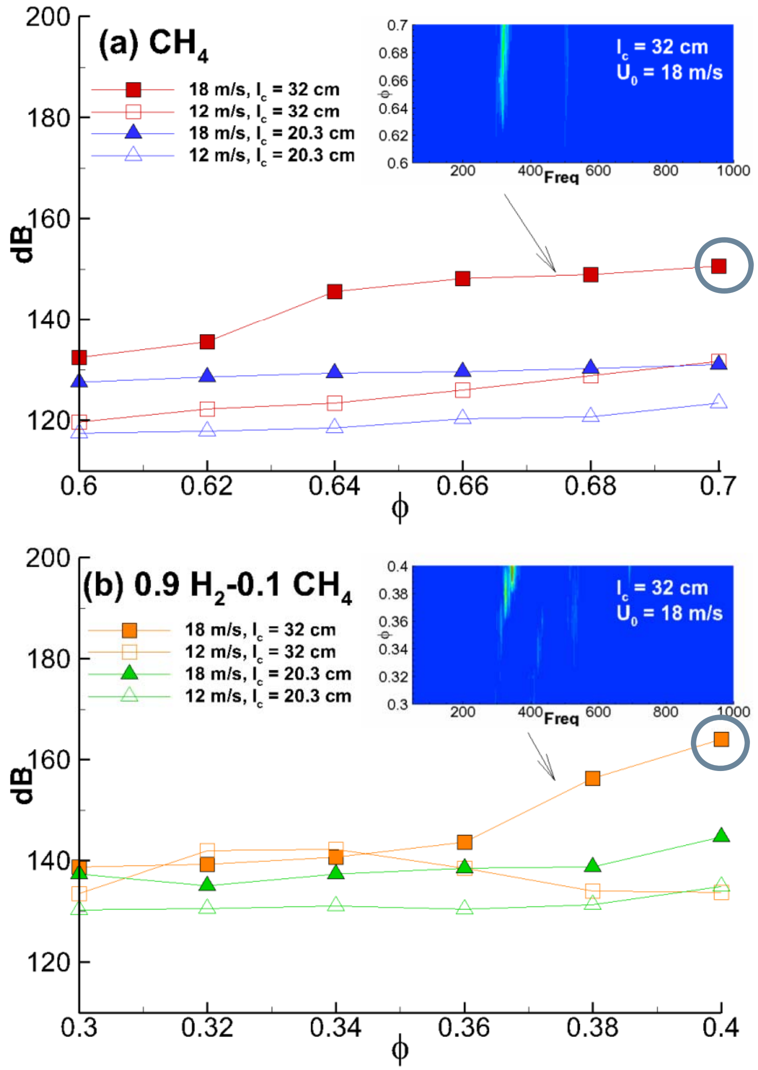
100%CH_4, Φ 0.6
U_o 18 m/s, T_{ad} 1670 K

90%H_2/10%CH_4, Φ 0.3
U_o 18 m/s, T_{ad} 1150 K

90%H_2/10%CH_4, Φ 0.4
U_o 18 m/s, T_{ad} 1385 K

- CH4 flame impinges on combustor wall.

- ϕ 0.4 H2 flame attaches to injector exit.
- **Burning in OSL increases flame acoustics.**

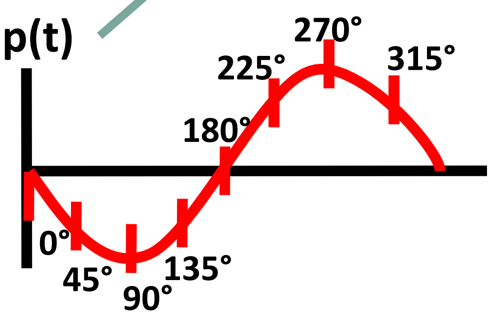


High sound levels of some of the LSI flames (exceeding 140 dB) show them to be thermo-acoustically unstable

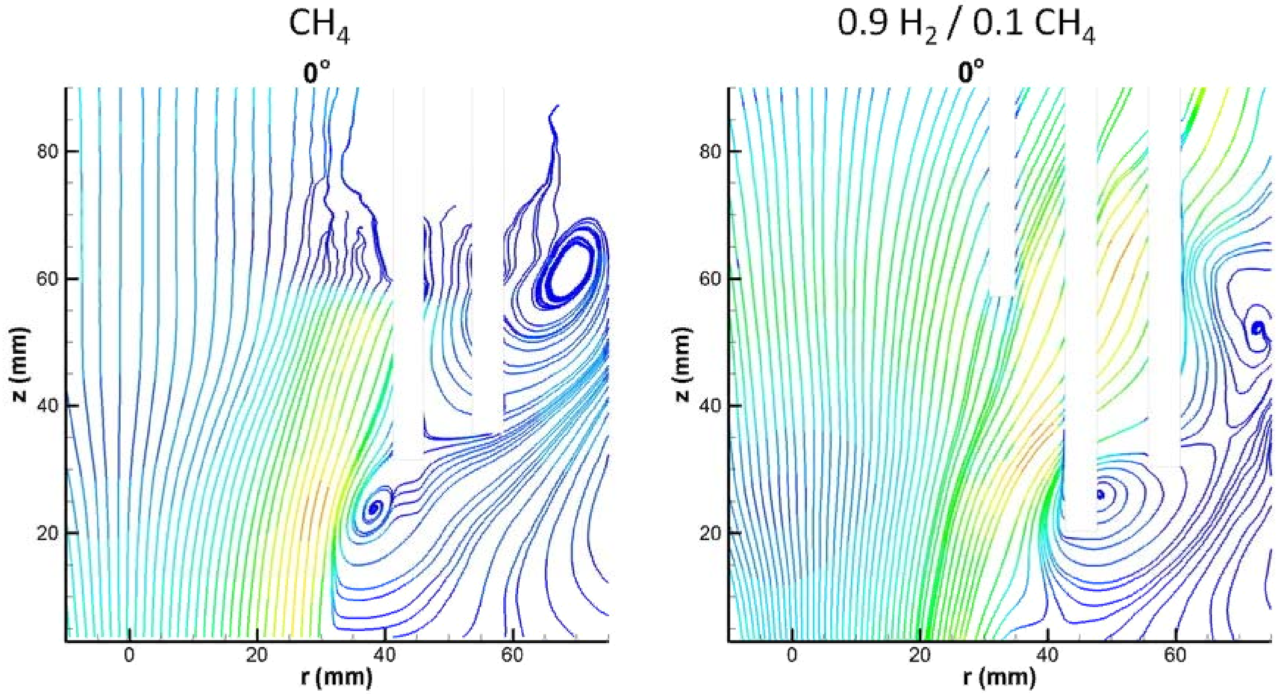
Pressure and Flame Crossing Spectra

- Pressure frequencies corresponds to flame oscillation frequencies
- “Coherent” flame movements dominate the outer shear layer
- “Coherent” flame movements not observed in the central region
  - except for the 0.9 H_2 flames that are attached
- Selected two baseline flames for phase-resolved PIV study

Examined Shear Layer Structures to Understand Unsteady Flow/Flame Coupling



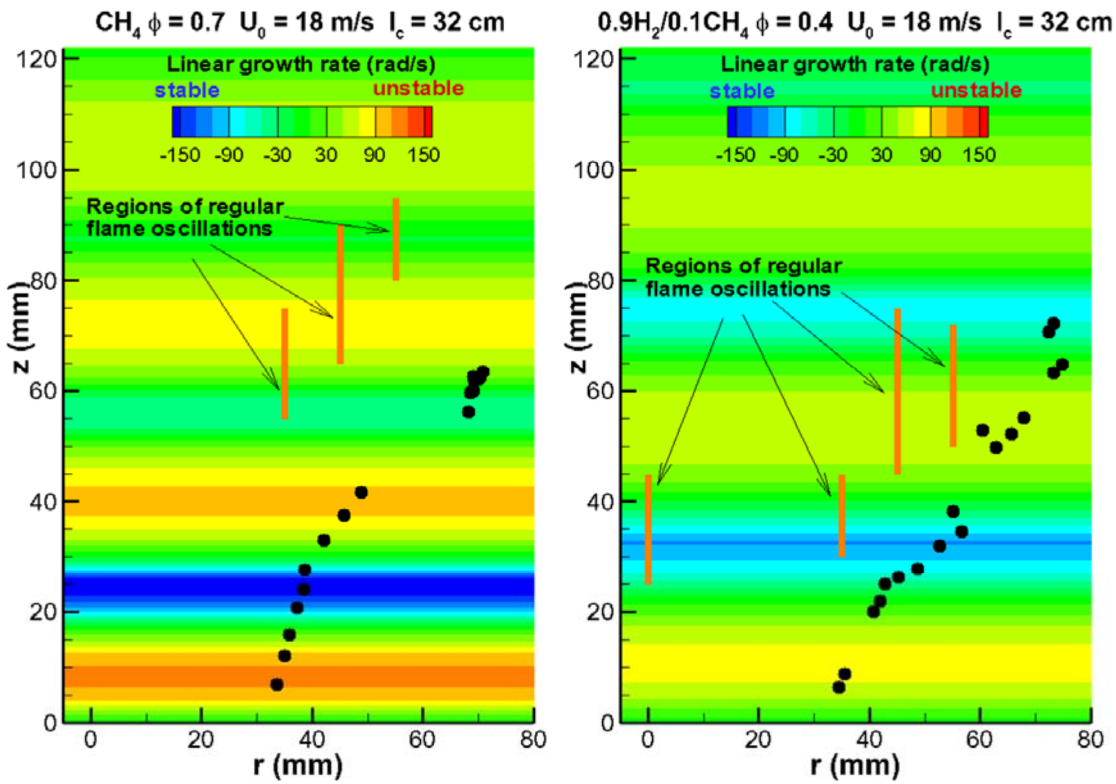
Pressure signal at the swirler was used to trigger phase resolved PIV sampling at eight phases per cycle.



- Ring vortices convect in outer shear layer.
- For CH_4 flame - convecting vortex merging with standing vortex
- For 90% H_2 flame – vortices escape from flame zone

BERKELEY LAB

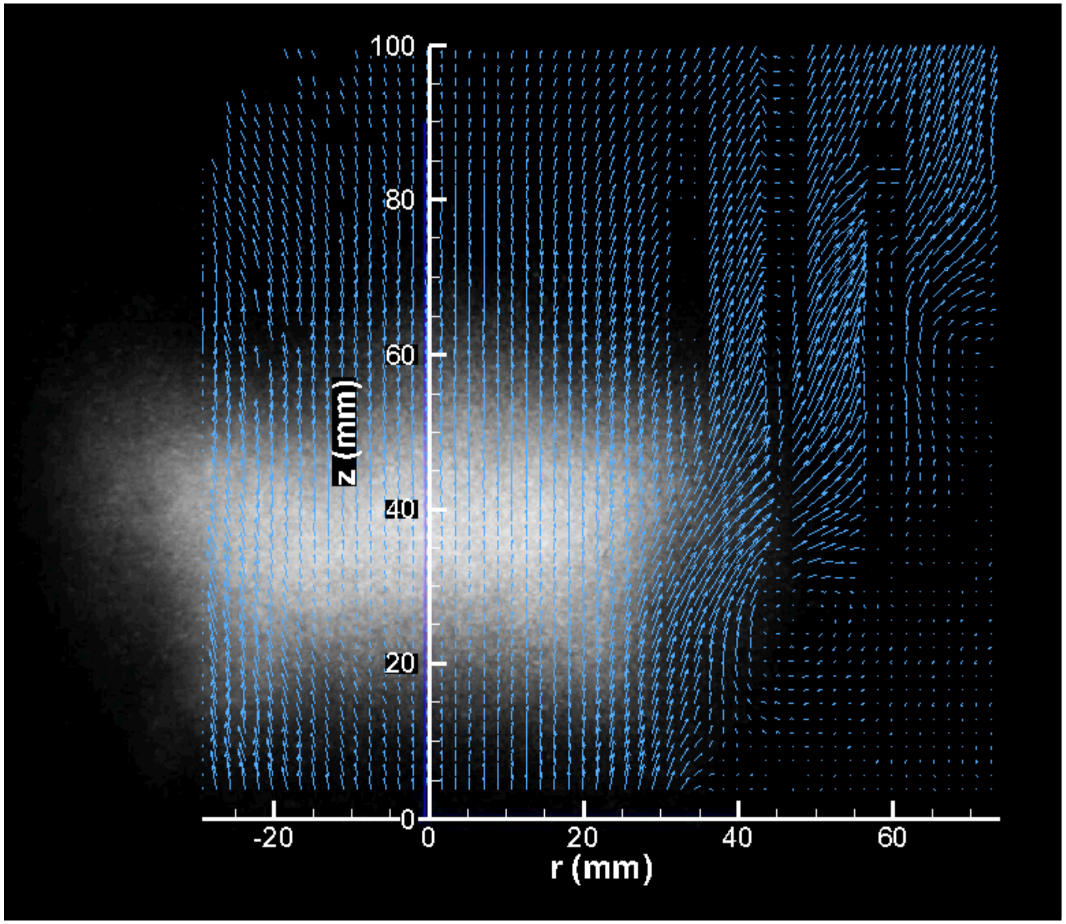
Phase-Resolved PIV Data As Inputs for General Instability Model Analysis



Trajectories of the vortex centers (black dots) from PIV provides empirical inputs for GIM analysis of the linear growth rates (horizontal color bands) of the unstable system. Observed flame instabilities (orange bars) are found to occur at the unstable region

- Time delay data for General Instability Model (GIM) deduced from phase-resolved PIV
- GIM predicts linear growth rates of the unstable system
  - For CH_4– flame oscillations coincide with GIM unstable band showing the vortices to be the controlling instability mechanism
  - For 90% H_2 flame – less conclusive results due to flame attachment
- Journal publication under review

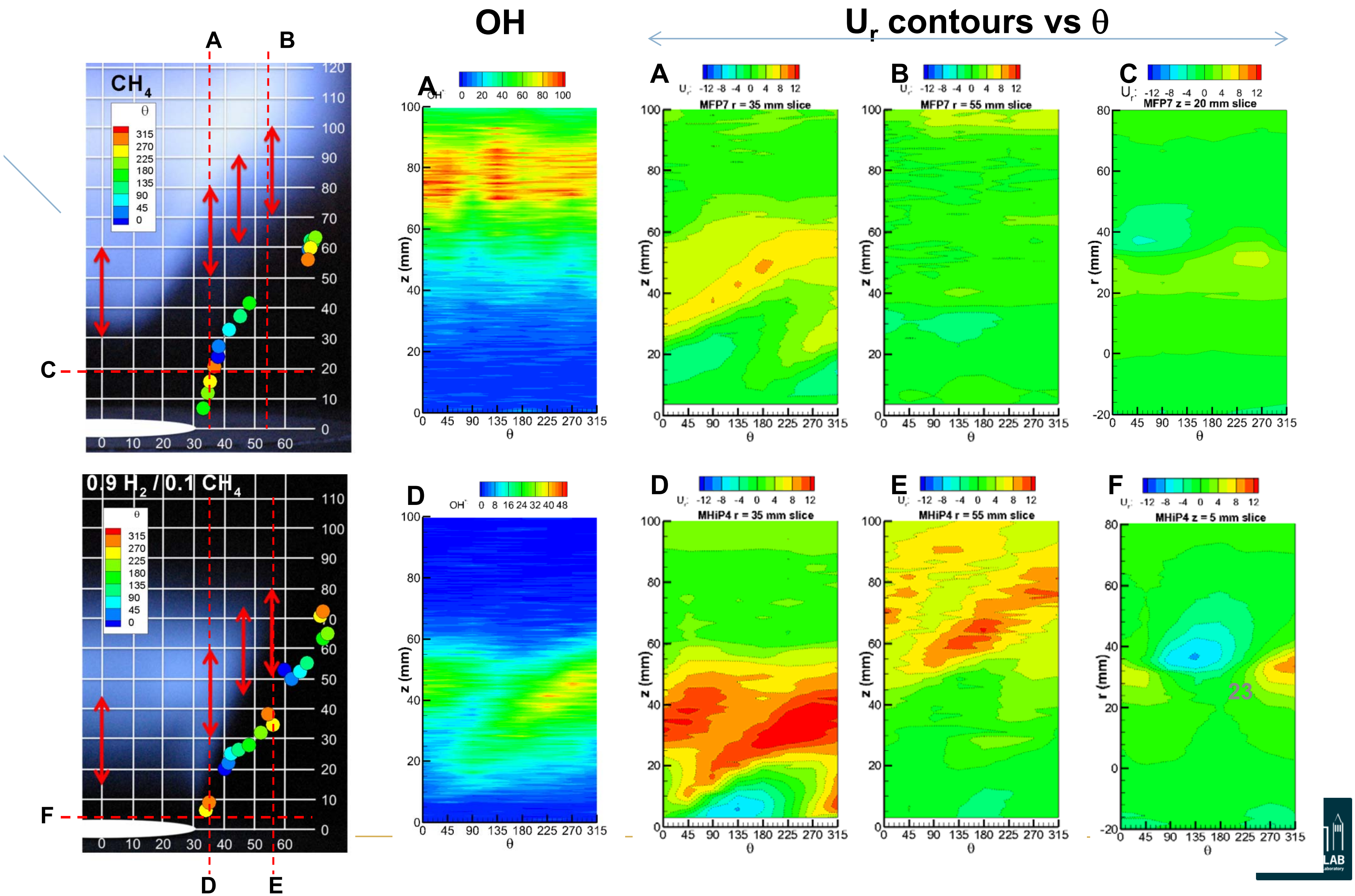
High Speed Imaging of Unstable Heat Releases of CH_4 and 0.9 H_2/0.1CH_4 Flames



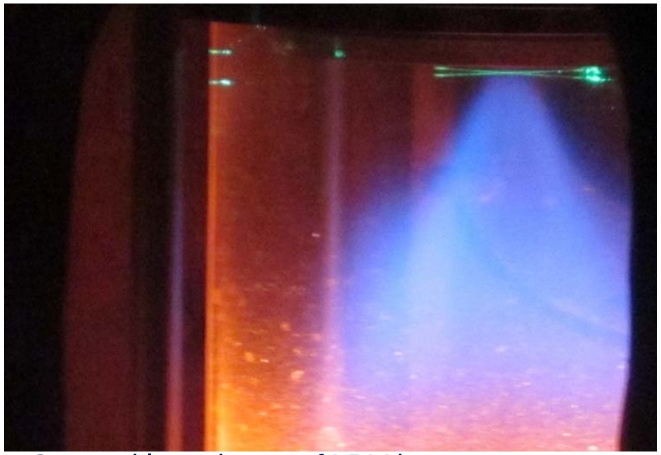
- Spectral behavior captured by high-speed imaging (4K Hz) of OH chemiluminescence
  - Obtained data for a series of flames
- Phase dependent heat release profiles deduced from Proper Orthogonal Decomposition (POD) analyze
- Comparison with phase-resolved PIV examines coupling of unsteady velocity field with Rayleigh indices

UTC Proprietary

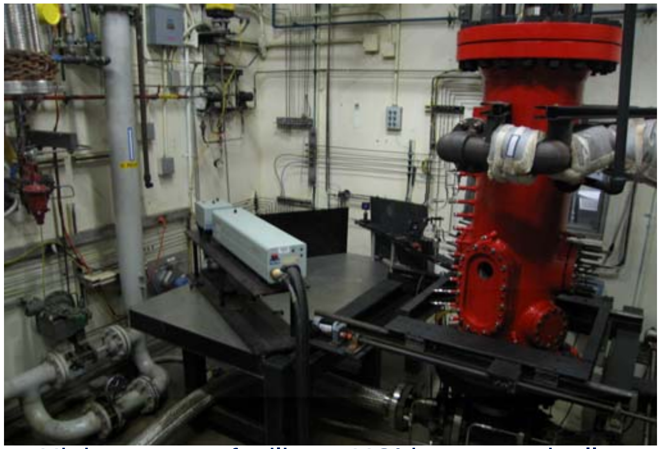
Phase Resolved PIV and OH Contours Show Correlation Between Flame and Vortical Structures



Turbulent Displacement Flame Speed, $S_{T\text{-}LD}$ at Gas Turbine Relevant Conditions



Crossed laser beam of LDV is seen measuring the local velocity at the flame front



High pressure facility at UCI has an optically accessible chamber for laser diagnostics

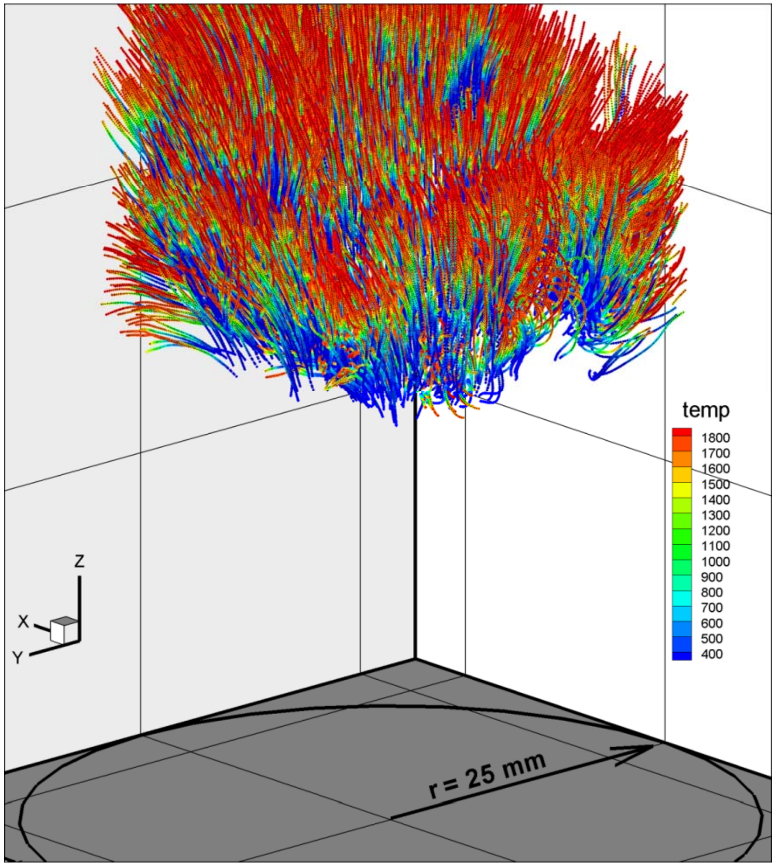
- Measurements of $S_{T\text{-}LD}$ require a large set of velocity statistics by spatially resolved laser method
  - Extremely challenging experiments performed in a high pressure combustion facility with optical access
- UC Irvine conducting S_T project for a Ph.D. thesis
  - Utilizing LSI designed and installed at UCI for a previous study on H_2 operability
  - Found solutions to address experimental challenges
  - Preliminary data very encouraging

BERKELEY LAB

Symbiotic Experimental/Numerical Studies to Investigate Lean Premixed Turbulent H_2 Flames

- Collaboration with LBNL Center for Computational Science and Engineering (CCSE) at Computational Research Division
- Numerical Approach
  - Via CCSE's Low Mach Number Combustion (LMC) code
    - Has uniquely capable incorporating experimentally relevant domain $(25\ cm)^3$ with detailed chemical kinetics, transport & efficient adaptive numerical methods
    - Requires DOE-BES "INCITE"-level resources on ORNL's JaguarPF supercomuter
- Challenges
  - Need to establish tremendous confidence in simulations
  - Large amount of simulated data requires new diagnostics and experimentalists' perspective to analyze

Extracting Insights from LMC Results

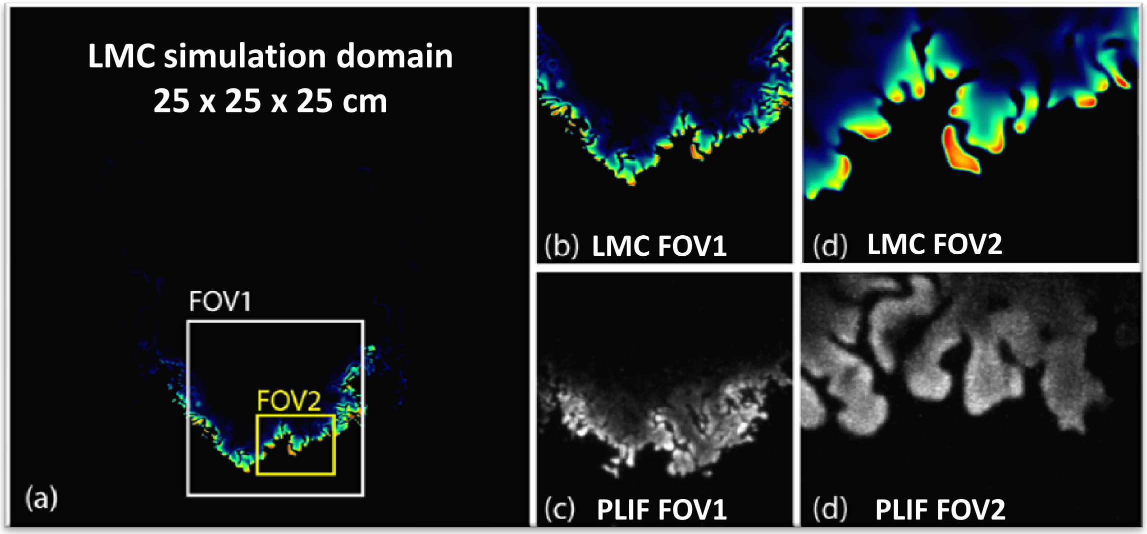


A new Lagrangian tracer method has been developed for analyzing LMC simulations of the LSB flames. Properties along the tracer paths through the flame (e.g. temperature as show above) are better suited for elucidating H_2 flame behavior than the conventional iso-surface approach

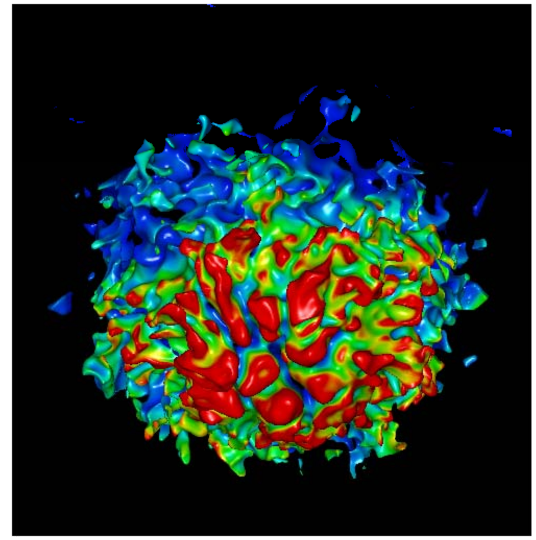
- New diagnostics are being developed for the high dimensionality, large simulation datasets to support the development of turbulent flame models
- Recent diagnostics:
  - "Flame-surface" (isotherm) statistics
  - Joint correlations (flame curvature, strain)
  - Flame-normal analysis of dynamics in flame frame
  - Lagrangian tracer statistics – flame dynamics in the frame of the fluid
- Paper reporting new diagnostics on CH_4 flames to appear in Comb. & Flame

BERKELEY LAB
Lawrence Berkeley National Laboratory

H_2 Turbulent Flame Structures Do Not Conform to Classic Wrinkled Flamelet Assumption



Simulated and measured instantaneous OH concentrations of a H_2/air flame at U_o = 15 m/s, ϕ = 0.37 show gaps in the concave regions

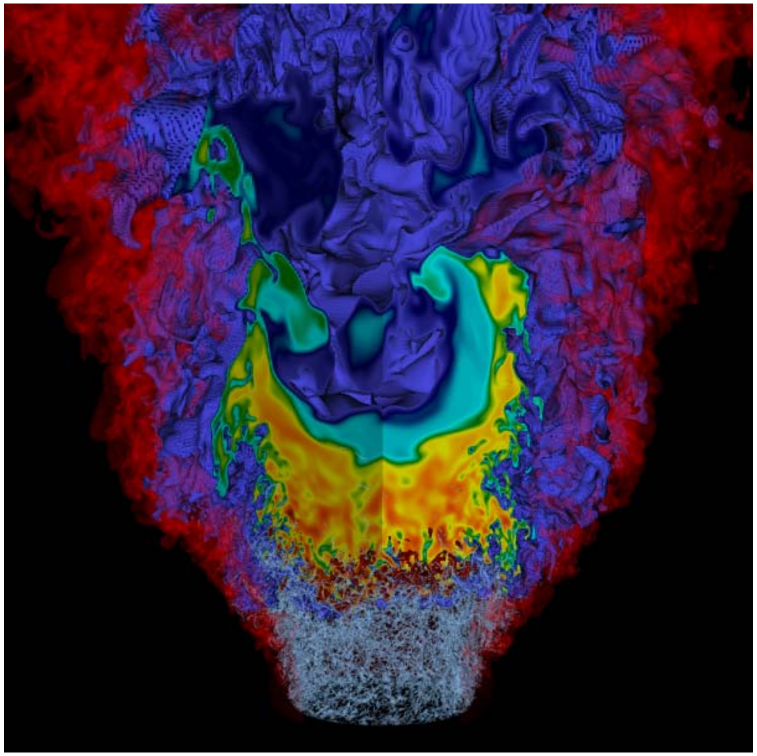


LMC simulation of a LSB H_2 flame show hot-spots in the convex regions

- H_2 flames have OH gaps due to thermal/diffusive instability effects
- Combustion models for non-uniform "discontinuous" flame front are not available
- Largrangian tracer analysis on simulated results is developed specifically to define proper modeling treatments for H_2 flames

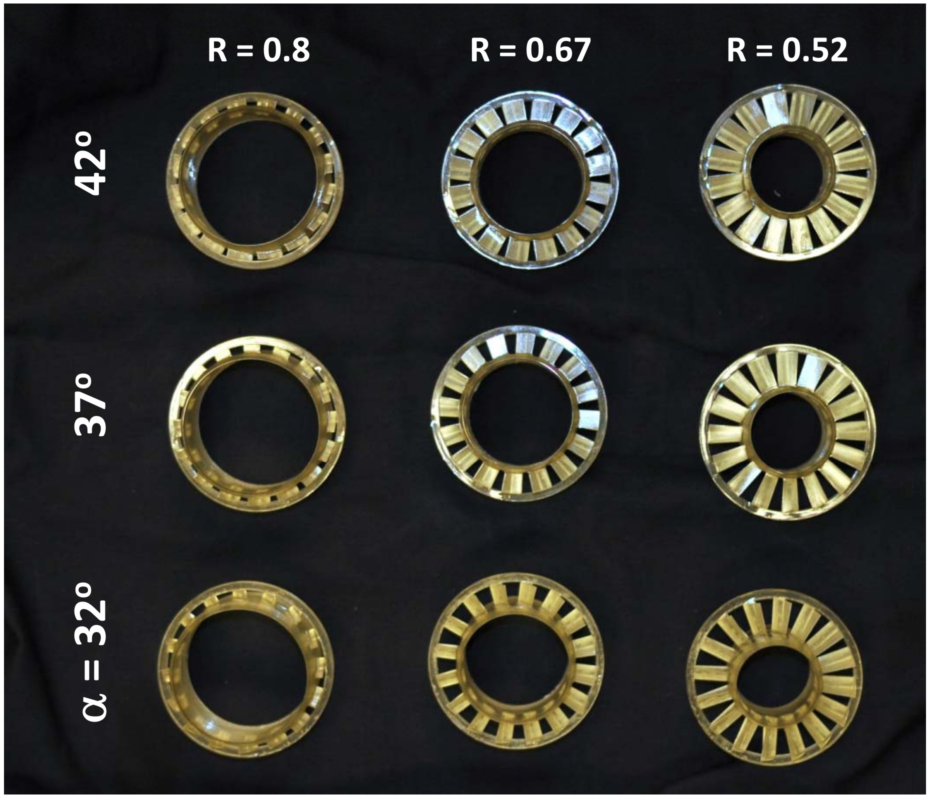
Next Step for LMC: Pollutant Formation in Lean Premixed Hydrogen Flames

- NO_x formation in cellular flames may explain 1 ppm NO_x 'floor' of H_2 flames
  - Enhanced burning, local enrichment results from high H_2 diffusivity
  - Simulation quantifies the formation of non-uniform NO over flame
- Other fundamental issues of H_2 flames:
  - Rethink the "flame front" concept
  - Applicability of 1D steady flame model
  - Limits of experimental validation



Isovolume showing X(NO) with fuel boundary (red) and vorticity from swirl (grey)

Parametric Study on LSI Swirler Configuration to Augment Design Guidelines for Gas Turbines



- Comparing performances and flowfields of ten LSI swirlers
  - $32^0 < \alpha < 42^0$
  - $0.52 < R < 0.8$
  - Thick & thin curved vanes
- Initial findings
  - LBO insensitive to swirler geometry
  - swirl number directly proportional to vane angle
  - $\Delta P/P$ drops with reducing R

Planned Activities:

- Augment Design Guidelines for LSI
  - Laboratory experiments on 9 variants of basic vane LSI swirler
- Characterize LSI Flame Instabilities
  - Continue collaborations with Siemens and UTRC
- Local Displacement Turbulent Flame Speed
  - Complimentary experiments at UCI and LBNL
- Investigate Local Structures of CH_4/H_2 Turbulent Flames
  - Flowpath analysis of simulated LSB flames