Low-Swirl Injectors for High Hydrogen Fuel Gas Turbines

Robert K. Cheng

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

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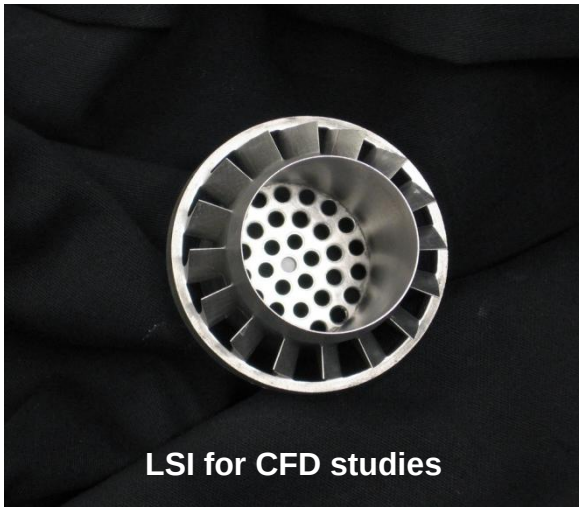
Participants and Collaborators

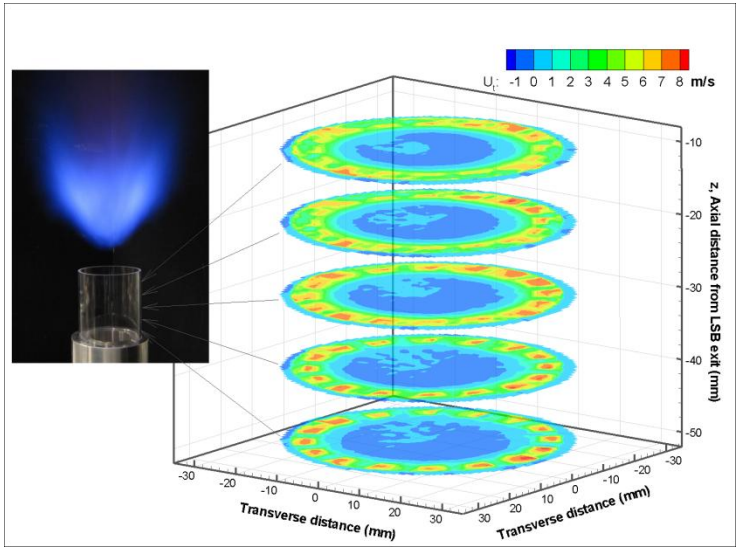
- LBNL – Environmental Energy Technology Div.
  - Robert Cheng, David Littlejohn, Peter Therkelsen, Ken Smith & Sy Ali
- United Tech. Research Center – Pratt & Whitney Power Systems
  - Dustin Davis, Catalin Fotache & Richard Tuthill
- Florida Turbine Technologies
  - Russell Jones & Joe Brostmeyer
-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

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 high hydrogen fuel (HHF).
- 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

Low-Swirl Injector Background





- LSI operates on a non-recirculating flame stabilization concept conceived at LBNL
  - ≈30% of the reactants remained unswirled to inhibit recirculation
  - Supports stable ultra-lean premixed flames for NO_x reduction
  - Scalable design
- Industrial low-swirl burners since 2003
  - Low pressure drop design offering high turndown (up to 60:1 in lab tests)
  - Guarantee 4-7 ppm NO_x (@3%O_2)
- Rig-tested for gas turbines
  - LSIs for Solar's T70 (< 5 ppm NO_x @ 15% O_2)
  - LSB pilot for Siemens F-frame combustor basket

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

- Desired fuel-flexibility features
  - Use natural gas for startup and as a 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 fuels (HHF) of 80% to 90% H_2 produced by water-shift reaction of syngases
- Emissions, operability, and cost tradeoffs
  - No one-size-fits-all solution

Technical Issues for Adapting LSI to H_2 Gas Turbines

- Scalability of the LSI to the size and power of utility gas turbines
- Fuel-flexibility of the LSI to operating with natural-gas, syngases, and HHF (3-fuel) without requiring significant hardware changes, moving parts, or elaborate controls
- Mitigating combustion dynamics and H_2 flame flashback and auto-ignition risks, as well as addressing issues specific to H_2 flame behavior
- Feasibility of designing an integrated and fully-functional LSI module that satisfies the specific requirements of the gas turbine system
- Adaptability and compatibility of the LSI with the control protocols of the HHF gas turbines and the IGCC plants

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First Step - Demonstrate Fuel Flexibility

- Laboratory experiments on natural gas, syngases, and H_2 flames at atmospheric conditions (LBNL)
  - Flowfield measurements, stabilization limits, turbulent flame speeds, emissions, flame shape, and flame acoustics
- Rig-test of sub-scale LSI swirler with syngases (Georgia Tech.)
  - $20\% < H_2 < 56\%$, $25\% < CO < 60\%$, 9%, $CH_4 < 51\%$, $450 < T < 550$ K, $P = 8$ atm, $20 < U_0 < 30$ m/s
  - Flame stability limits, flame shape
- Rig-test of LSI swirler using natural gas and H_2 (NETL)
  - $0\% < H_2 < 100\%$, $0\% < NG < 100\%$, $20 < U_0 < 40$ m/s, $2 < P < 8$ atm
  - Flashback, flame shape, emissions
- Results reported in three journal papers
  - Analytical model describing fuel effects
    - Coupling of flowfield self-similarity and linear dependency of local displacement turbulent flame speed on turbulence intensity
  - NO_x emissions decrease long linearly with adiabatic flame temperature, T_{ad}, except for HHF flames with a 1 ppm "floor" at $T_{ad} < 1600$K

Insights from Fuel Effects Studies

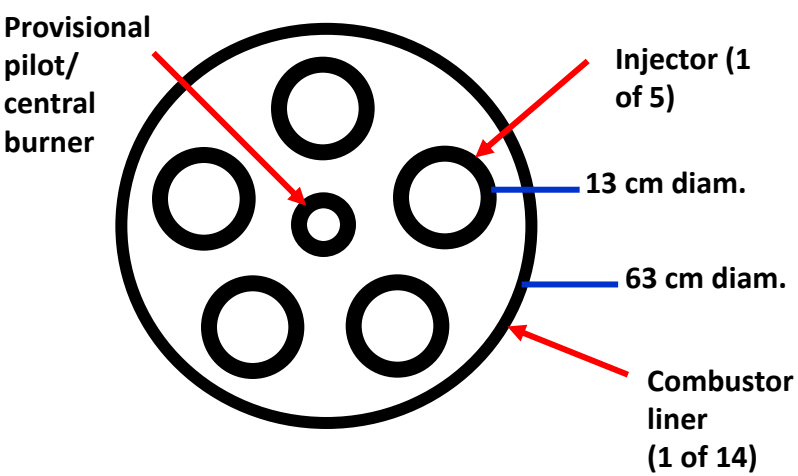
- Basic LSI principle amenable to fuel-flexible operation without requiring hardware adjustment, i.e. movable parts
- Flame positions unaffected by bulk flow velocity, T_0, P_0 and fuel/air ratio
- H_2 flames burn at higher turbulent displacement flame speeds
  - upstream shift in flame position
- Inner shear flow regions are flashback paths for H_2 flames
- Outer shear and recirculation promote H_2 flame attachment
  - Alters flame stabilization mechanism
- 1 ppm "NO_x floor" from H_2 flames needs more studies

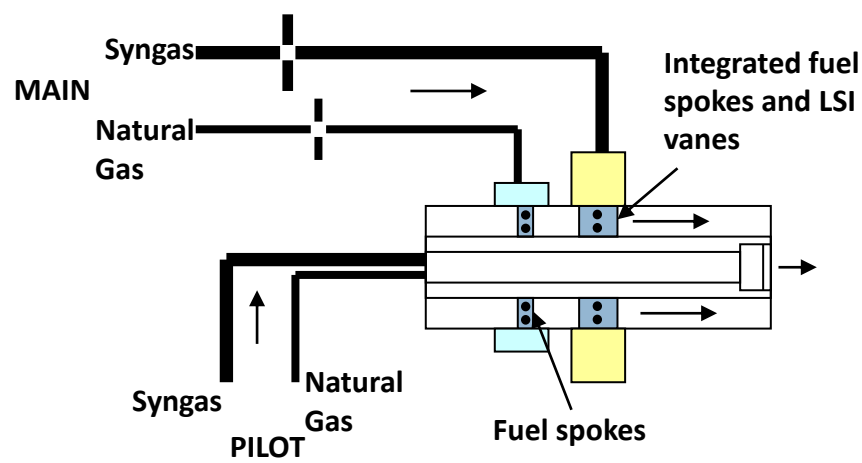
Feasibility Study of a 3-Fuel Low-Swirl Injector

- Goal
  - Evaluate the basic requirements of the fuel delivery and injection systems for a generic F-class LSI module to operate with the 3-fuels
  - Estimate the impact on turbine operation
- Approach
  - Fuel analysis – interchangeability of the fuel injection system
  - Combustion system characteristics – impact due to differences in fuel mass flow rates
  - Conceptual fuel injector design – balance between fuel-flexibility and design complexity
  - Operational considerations – staging and piloting

Conceptual Fuel Injection Design

- Preliminary design adopted with five injectors per can and central diffusion pilot for a typical F class gas turbines
- Pilot for start up, fuel transition, and mitigating combustion stability issues
- Fuel delivery to swirling air via axial spokes
- Fuel spokes designed based upon fuel flow, fuel pressure drop, and fuel distribution
- Two sets of spokes are proposed for LSI system, fed by two fuel circuits
- (1) NG and pure H_2, (2) HHF and syngases





Main Conclusions of 3-fuel Study Reported at TurboExpo 2010

- At least two parallel main fuel circuits to address the significant differences in Wobbe indices of natural gas, syngases and HHF
- Central pilot for each LSI may be needed to provide operational flexibility
- Flashback risk manageable with mixing distance < 10 cm
- Refinement of the LSI and a detailed assessment of the entire combustion system to be conducted after a candidate engine for prototype development is selected

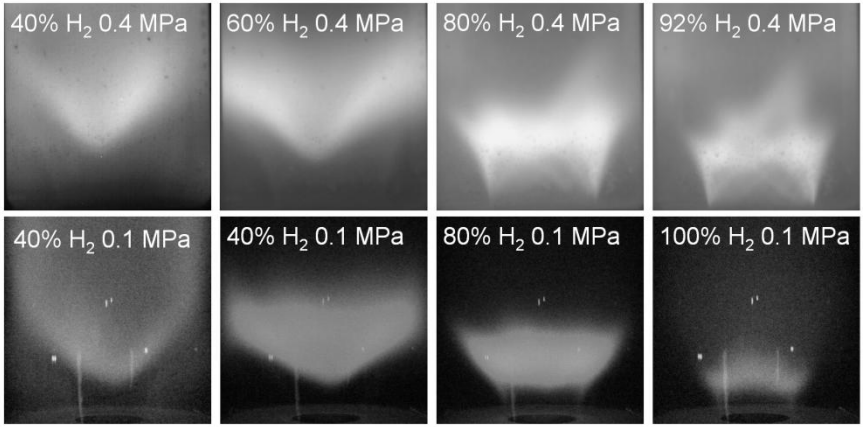
Engineering Issues and Challenges of a 3-Fuel LSI System

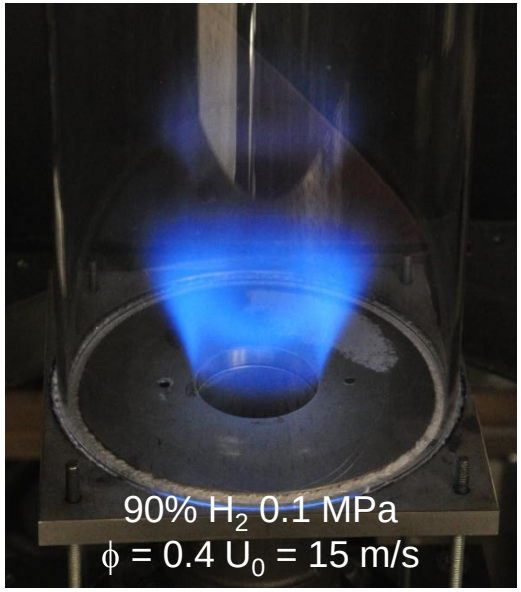
- **Combustor cooling** – Products gas temperatures and compositions changes with fuel and affect heat transfer rates in primary zone
- **Mixing length** – Possible tradeoff between mixture homogeneity and management of auto-ignition risk
- **Fuel spokes design** – Larger fuel spokes creating excessive pressure drops
- **Combustor volume** – Changes in flame volume with fuel composition affecting CO and NO_x formation
- **Combustor acoustic oscillations** – Wide range in fuel specifications may increase the propensity to incite combustion oscillations
- **Increase turbine flow** – Risk of gas turbine compressor surge due to larger syngas mass flow
- **Optimum syngas compositions** – cost/benefit of reducing fuel variability

Conceptual 3-fuel LSI Prototype Development

- UTRC/PWPS project commenced March 2010
- Scope-of-work
  - Task 1 Conceptual architecture of a 3-fuel LSI system and operation models
  - Task 2 Design candidate LSIs fitted with fuel injectors
  - Task 3 Prepare a test rig and facility for evaluation of a single reduced-scale LSI
  - Task 4 Verify LSI operation with HHF injector concept
- Progress
  - Tasks 1 and 2 complete
  - Task 3 on track

Modified LSI Nozzle for HHF Operation

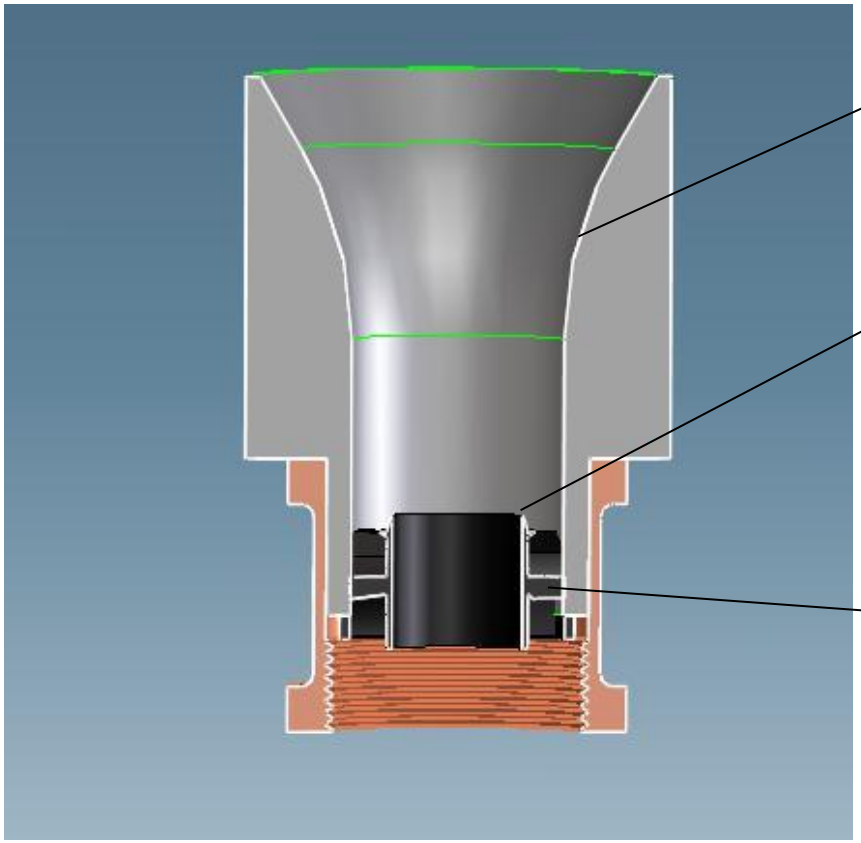




- HHF flames burn in the outer shear layer formed at the nozzle exit because:
  1. Flow separation at the sharp transition point produces intense shear turbulence
  2. Shear region becomes flammability due to high diffusivity and reactivity of H_2
- Burning in outer shear layer alters flame stabilization mechanism and LSI performance
- Problem cannot be addressed by straight edge divergent quarl
  - HHF flames burn in shear layer produce behind small abrupt transition in the flow paths

LSI with Flared Nozzle Optimized for HHF

- 3rd order polynomial profile mimic LSI flow divergence
- Sectional construction to evaluate impact of flared nozzle length on flame stability and range of operation

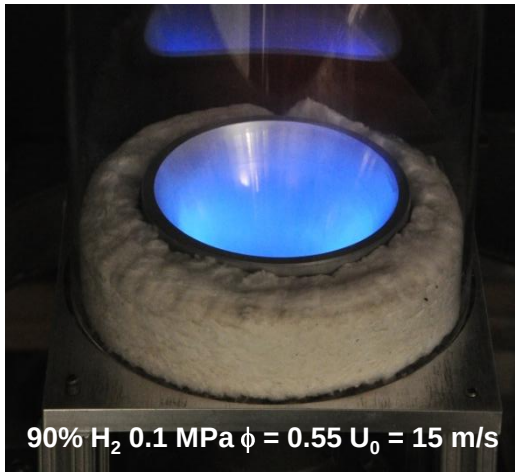


Flared nozzle with smooth divergence profile defers outer shear layer formation

Tapered center channel wall reduces turbulence in the inner shear layer generated by interactions of the swirled and the unswirled flows

Small vane angle reduces shear generated at the trailing edge

Flared Nozzle Extends HHF Operation



- Flared nozzle mitigates H_2 flame attachment
  - Extends operating rage of $0.9H_2/0.1CH_4$ to T_{ad} = 1700K (ϕ = 0.55) at U_0 = 15 m/s
  - Flame not in contact with nozzle wall
- Long flared nozzle (extending to the combustor wall) compromises operability
- Short flared nozzle preserves operability
- Mitigating shear layer burner reduces flame acoustic
  - LBNL/Siemens Energy Inc. collaboration
  - Study on the effects of shear layer and outer recirculation to be presented later
- Flared nozzle incorporated in the design of the conceptual 3-fuel LSI being developed jointly with UTRC/PWPS

Verification of HHF Operation at Simulated Gas Turbine Conditions

- Reduce scale LSI with flared nozzle fabricated for U.C. Irvine's down fired high pressure facility
  - 3.8 cm I.D. benchmark LSI (16 thick vanes, 37° blade angle) fitted with upstream fuel spoke injectors
- Preliminary verification tests with natural gas
  - $U_0 > 30$ m/s, $P > 9$ Mpa
- HHF (90% H_2) study commencing late October 2010

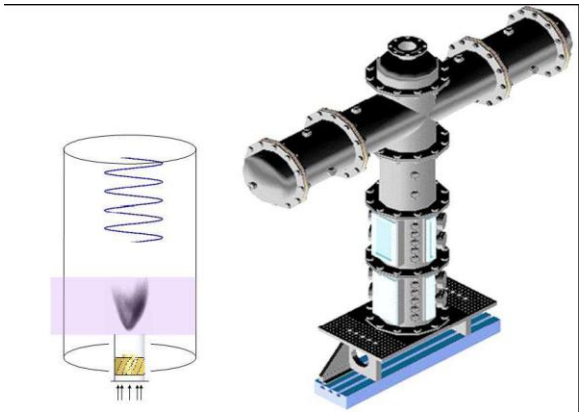
Scale-up LSI for Natural Gas Operation

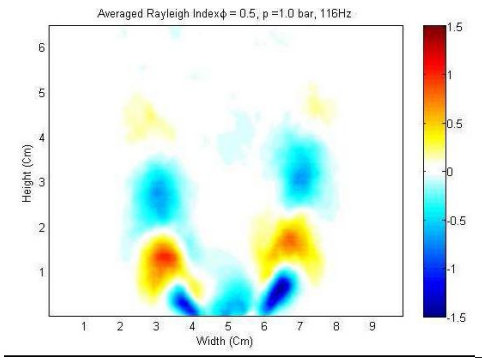
- Essential intermediate goal to gain practical experiences on LSI operating in a gas turbine system
- Initiating a collaboration with Florida Turbine Technologies to:
  1. Determine the size of the LSI for integration into a large industrial gas turbine
  2. Develop hardware for natural gas operation
  3. Assess and mitigate LSI-to-LSI interactions
  4. Conceptual design of a full-scale LSI for testing at atmospheric conditions

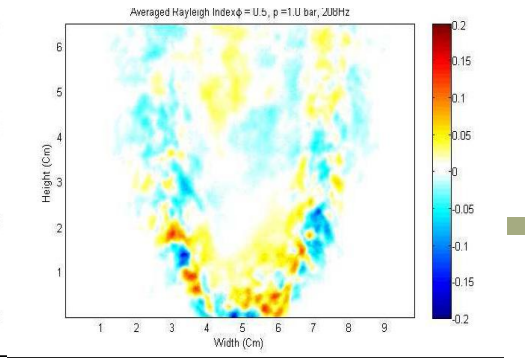
Core Technology Support Research

- LSI responses to acoustic perturbation
- LSI self-excited acoustics and implications on combustion oscillations
- Symbiotic experimental/numerical studies of thermal/diffusive effects in turbulent lean HHF flames

Studies of LSI Responds to Acoustic Perturbations at U. of Iowa







118 Hz **208 Hz**

Local Rayleigh Index

- Prior studies on CH_4 flames reported in three journal papers
  - Phase-resolved OH-PLIF show flame instability confined to outer shear region
- On-going study of CH_4/H_2 flames with a benchmark 1.5” LSB
  - Characterized pressure induced changes between 1 and 3 bar of 100% CH_4 to 100% H_2 flames
  - Measure and analyze
    - Flame Surface Density
    - Rayleigh Index
    - Transfer Functions
- Background PIV data for stable CH_4 and H_2 flames with and without divergent nozzle obtained at LBNL

LSI Self-excited Flame Acoustics

- Collaboration with Siemens Energy Inc.
  - Continuation of a study presented at TurboExpo 2010
- Compare acoustics spectra, flame oscillation spectra, and flowfields of LSI burning CH_4 and 90% H_2 – 10% CH_4
- Validate a Generalized Instability Model (GIM) that predicts dominant acoustic frequency of LSI combustion

Experimental Matrix with baseline conditions underlined		
Fuel	**100% CH_4**	**90% H_2 - 10% CH_4**
Equivalence Ratio (ϕ)	0.6 & **0.7**	0.3 & **0.4***
Bulk Flow Velocity U_0	10, 15 & **18 m/s**	10, 15 & **18 m/s**
Exit Geometry	**Dump Plate** & Flared nozzle	**Dump Plate** & Flared nozzle
Adiabatic Flame Temperature	1669 & **1847 K**	1151 & **1384 K**

*** ϕ of 90% H_2 – 10% CH_4 restricted to ≤ 0.4 to avoid flame attachment**

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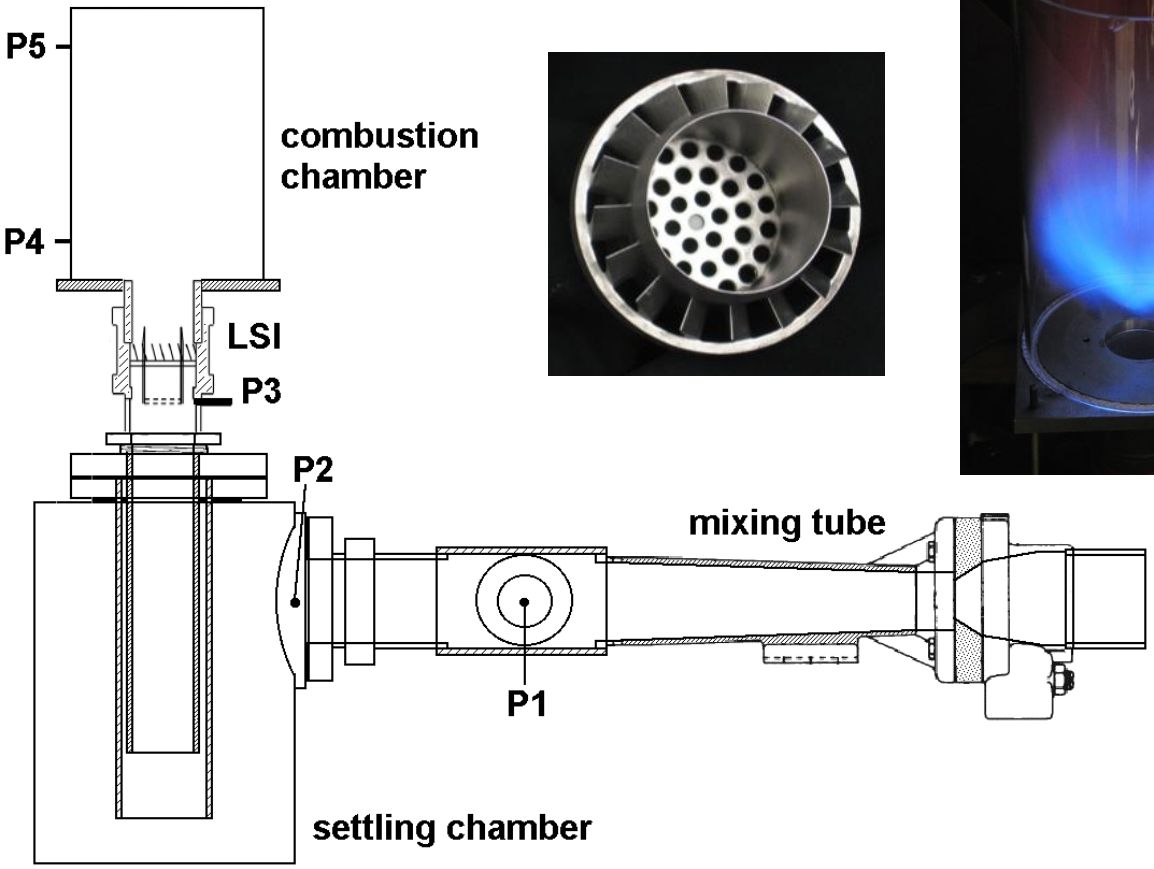
Experimental Setup

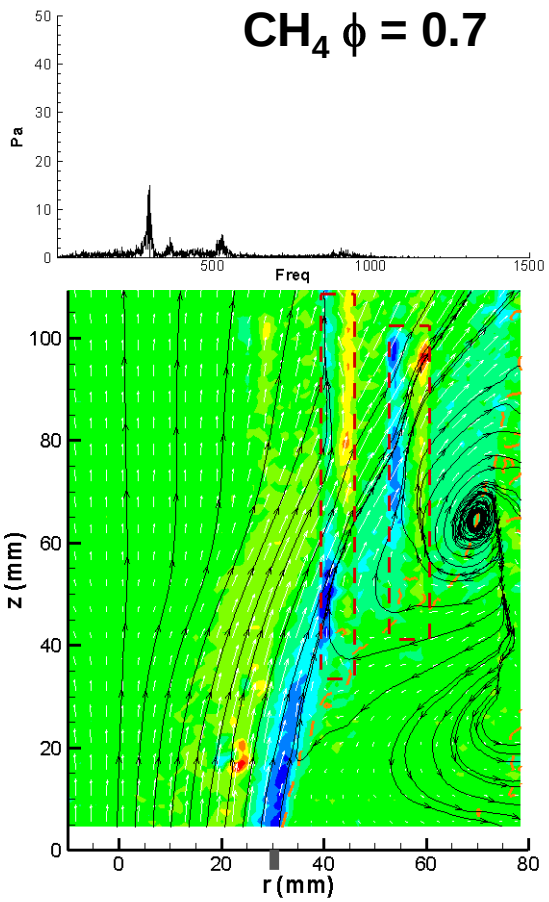
- Well-mixed atmospheric blowdown system of 0.16 to 1.05 kg/s air (unchocked) into a facsimile of SimVal combustion chamber with 5 pressure taps P1 - P5
- Open end 32 cm long, 18 cm i.d. cylindrical enclosures (quartz for PIV, stainless steel for pressure measurements) with sudden expansion

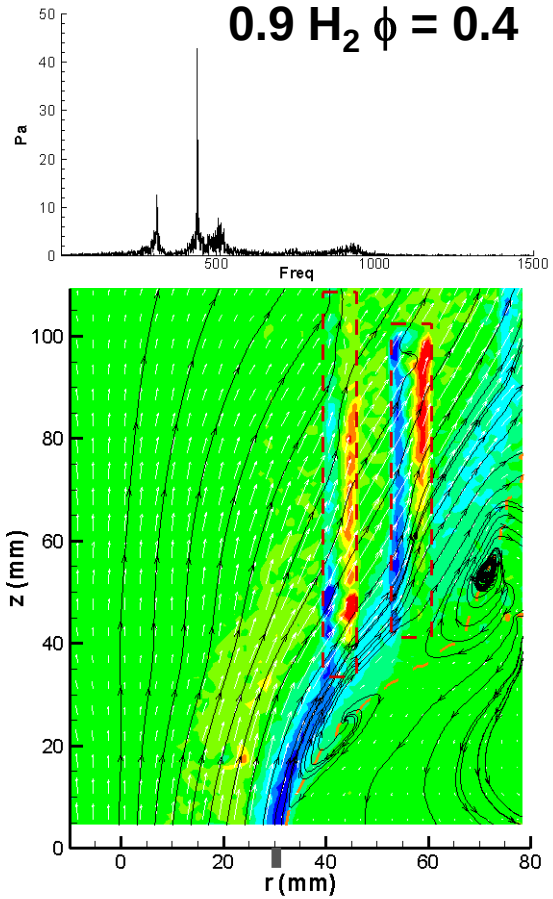


Diagnostics

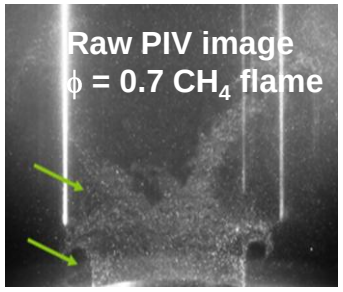
- Acoustic frequency spectra
  - Honeywell SPTMV0003PG pressure transducer on combustor can (P4)
    - 0 to 3 psig full-scale range and 0.1 ms response time
    - Keithley 427 amplified signal digitized at 5 kHz
- Flame fluctuation/oscillation spectra
  - Line-of-sight schlieren based laser beam deflection
    - Position-sensitive diode for recording deflected light frequencies at 5000 Hz
    - Spectrum of diode signal contains turbulent flame fluctuations (broad band) and discrete flame oscillations (narrow peak)
    - Scan various flame regions to detect flame oscillations
- Velocity statistics
  - Particle Velocity Imaging (PIV)
    - New Wave Solo PIV laser – Kodak/Red Lake ES 4.0 camera –
    - 13 x 13 cm field-of-view from center to corner
    - Analysis conducted with 224 image pairs
    - Pressure fluctuation phase-locked PIV in progress

Flowfield and Acoustic Spectra of CH_4 and 90% H_2 Flames at U_0 = 18 m/s

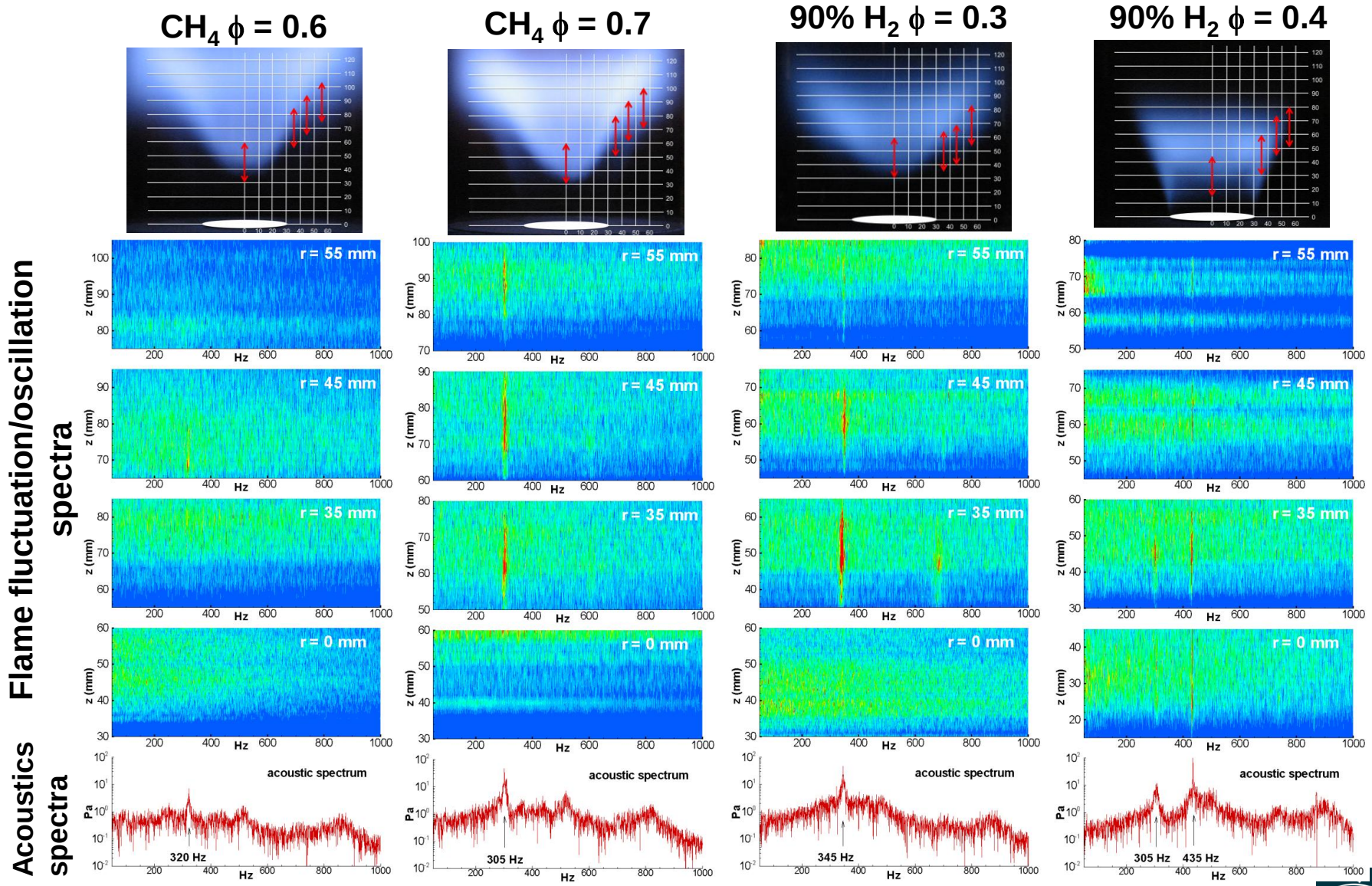




- 90% H_2 flame with lower total heat release generates higher acoustic pressure fluctuations at a higher frequency than the CH_4 flame
- Flame impingement on combustor wall generates a second flow recirculation zone above the corner

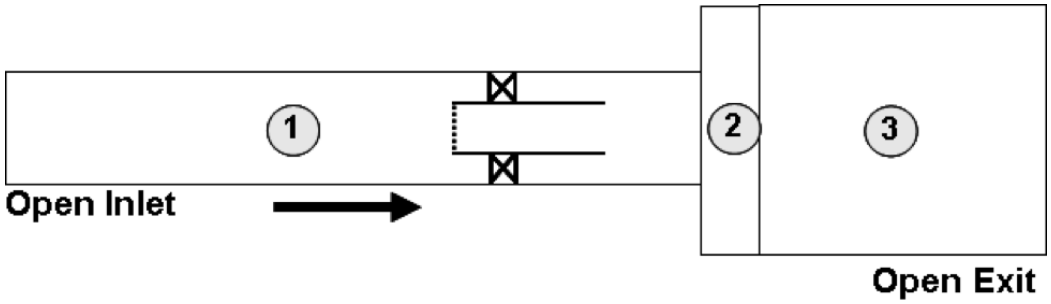


Flame Oscillations Corresponds to Acoustics

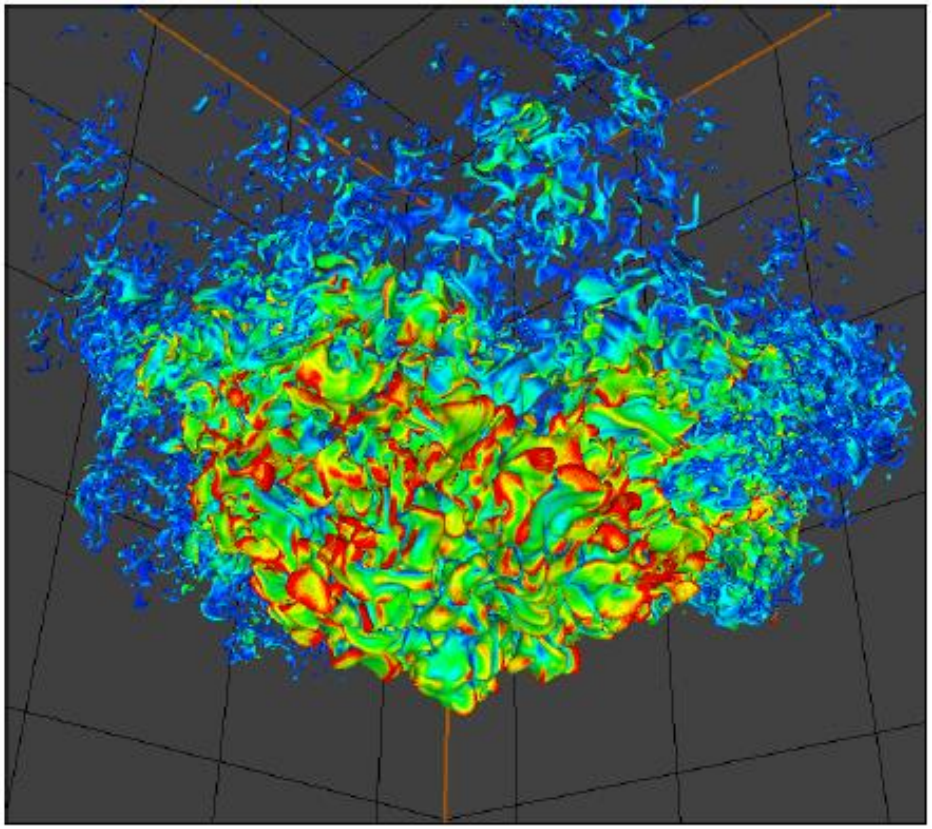


Preliminary Assessment of Self-excited LSI Thermoacoustics Behavior

- Flame oscillation frequencies correspond to acoustic frequencies
  - For lifted flames, flame oscillations occur at the outer shear layer
    - flame impingement on the combustor wall may cause local quenching
  - For attached flames, oscillations also occur at the center region at a frequency corresponding to the highest fluctuating pressure frequency
- Changes in the fluctuating flame behavior to be used as input for a General Instability Model (GIM)
  - Approximate burner and plenum as an acoustics system with open boundaries
    - Solved for the temporal instability of the system by calculating the eigenfrequencies of a wave equation using the Galerkin method
  - First analysis presented at TurboExpo 2010 show flame excited frequencies of (300 to 320Hz) correspond to 1L mode frequency of the acoustic system



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



Local heat release rate of H_2 flames can be 3.5 times higher than the heat release rate based on global stoichiometry. This may explain the 1 ppm NO_x "floor" found at NETL

- H_2 turbulent flame models for high-fidelity CFD is lacking
- Numerical results can provide useful insights to develop new models
  - Complex 3D flame structures cannot be captured by the best available laser diagnostics
- Center for Computational Science and Engineering at LBNL specializes in large domain (25 cm^3) 3D time-dependent direct numerical simulation of turbulent premixed flames
- Low-Mach-number adaptive-mesh-refinement code (LMC) integrates multi-species Navier-Stokes equations with chemical kinetics
  - Resolved detailed reaction front structures in a physically meaningful domain

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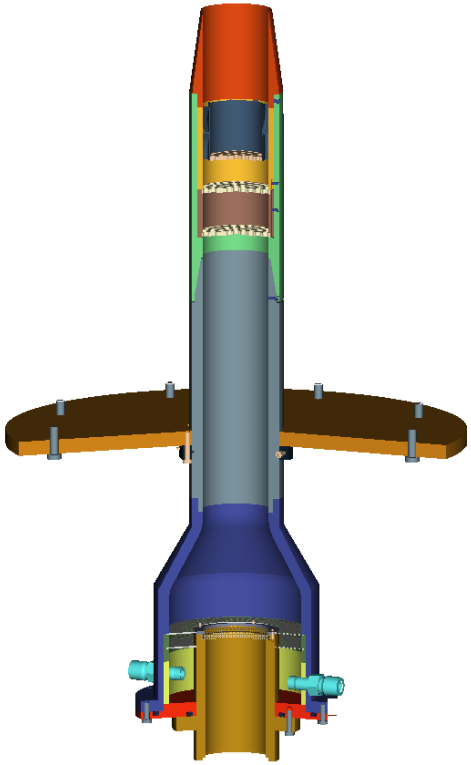
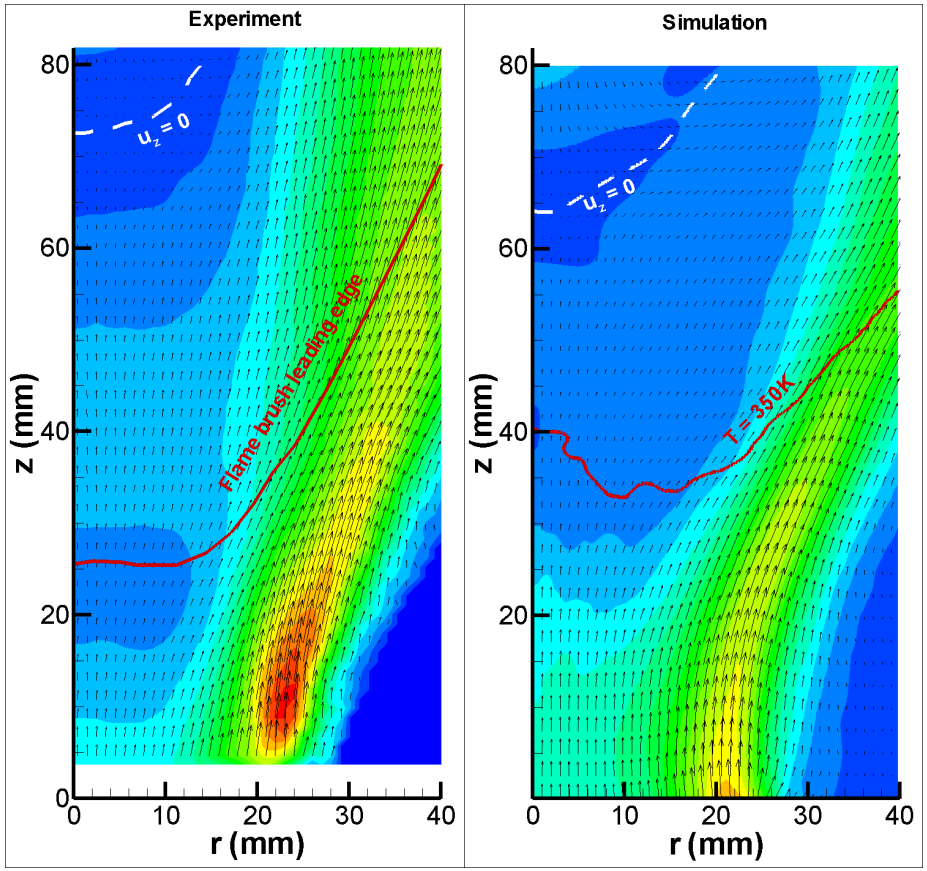
LSB for OH-PLIF, PIV & LMC Simulation of CH_4 and H_2 Flames



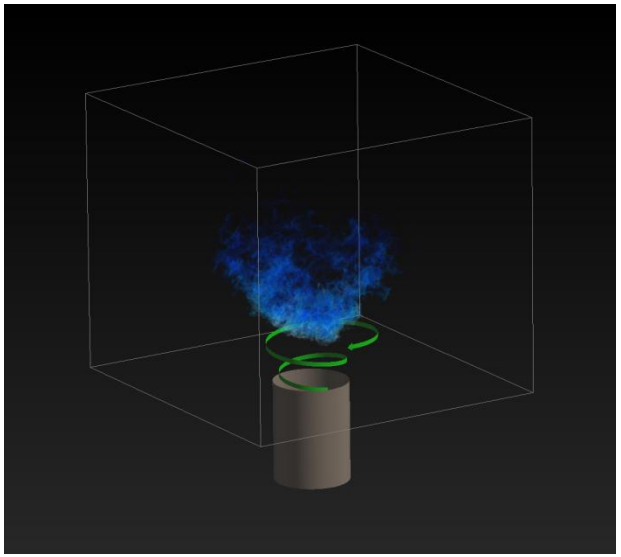
Darmstadt/Lund/LBNL LSB for fundamental premixed turbulent flame studies

- Darmstadt/Lund/LBNL joint development
  - 5 cm i.d. burner with co-flow
  - facility high-power laser diagnostics
  - standard configuration for data exchange and sharing
- OH-PLIF and PIV measurements of CH_4, CH_4/H_2 & H_2 flames at $3 < U_0 < 18$ m/s
- LMC simulation of 2 CH_4 flames, 2 H_2 flames & 5 CH_4/H_2 flames at 10 and 15 m/s
- Experiments and simulations analyze the same way
  - 2D information on mean flame statistics (Σ, S_T, etc.), and flame wrinkle geometry
  - 3D time-dependent analysis of LMC simulated local flame structures to elucidate dynamic flame properties
- 3 publications planned

Validation of LMC Simulations

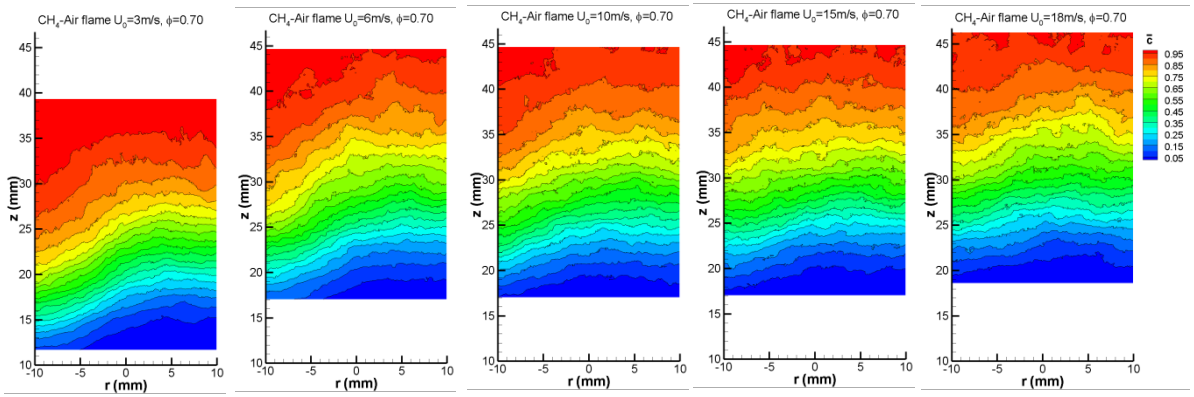


Measured and simulated flowfields of a CH_4/air flame at ϕ = 0.7 and U_0=15 m/s

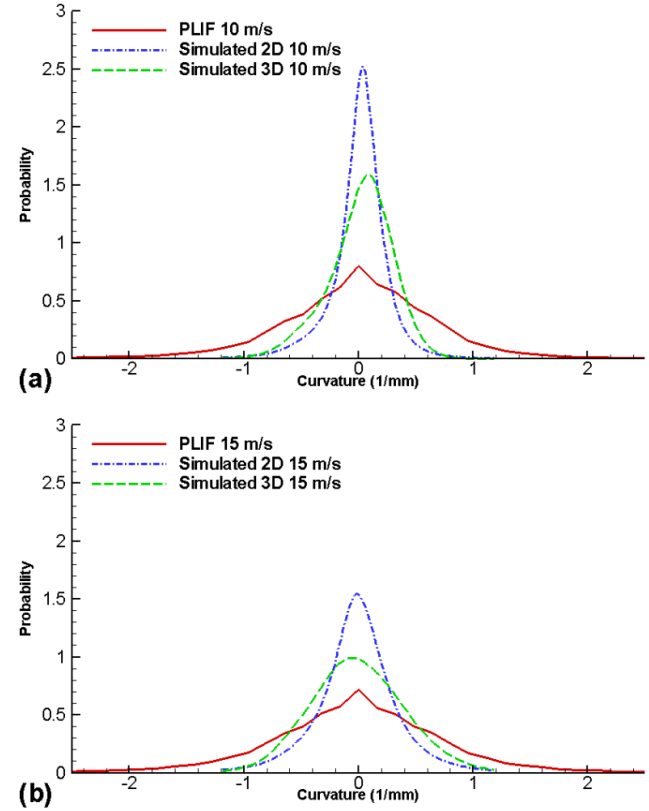


- LMC captures the salient features of the flowfield and its evolution with Reynolds number
- Discrepancies are attributed to the use of an azimuthally uniform inflow velocity
- Simulated results are sufficiently stable for detailed analysis of the local flame front properties associated with the shorter time scales

OH-PLIF of CH_4 flames and Comparison with LMC



- Contours of mean progress variable deduced from OH-PLIF show turbulent flame brush thickness invariant with U_0
- implies increase in flame surface area



- 2D flame curvature from OH-PLIF provides quantitatively comparison with 2D and 3D flame curvatures from LMC

Extracting Flame Front Dynamic Information from LMC Results

- Large amount of simulated data require detail interrogation to extract information to elucidate dynamic turbulent flame phenomena and for modeling development
  - Same treatment as diagnosing real physical flames
    - Mathematicians lack experience in studying combustion phenomena to lead the analysis
  - Availability of time-dependent 3D information offer unique opportunities and also new challenges
    - New algorithms to navigate through very large amount of data
    - Analysis methods for 2D time-independent experimental data are inadequate and can produce ambiguous results
- Fresh approaches needed to analyze LMC results
  - Iso-surfaces methods used to analyze DNS results will not produce useful information on H_2 flames due to ambiguities associated with thermal/diffusive effects

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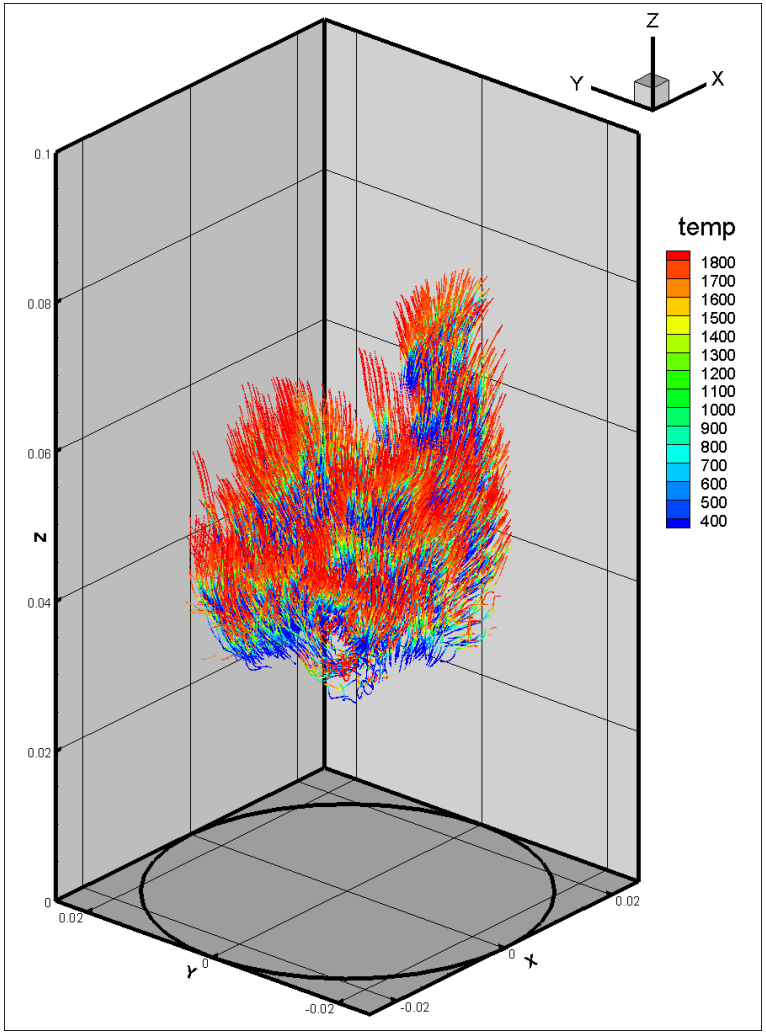
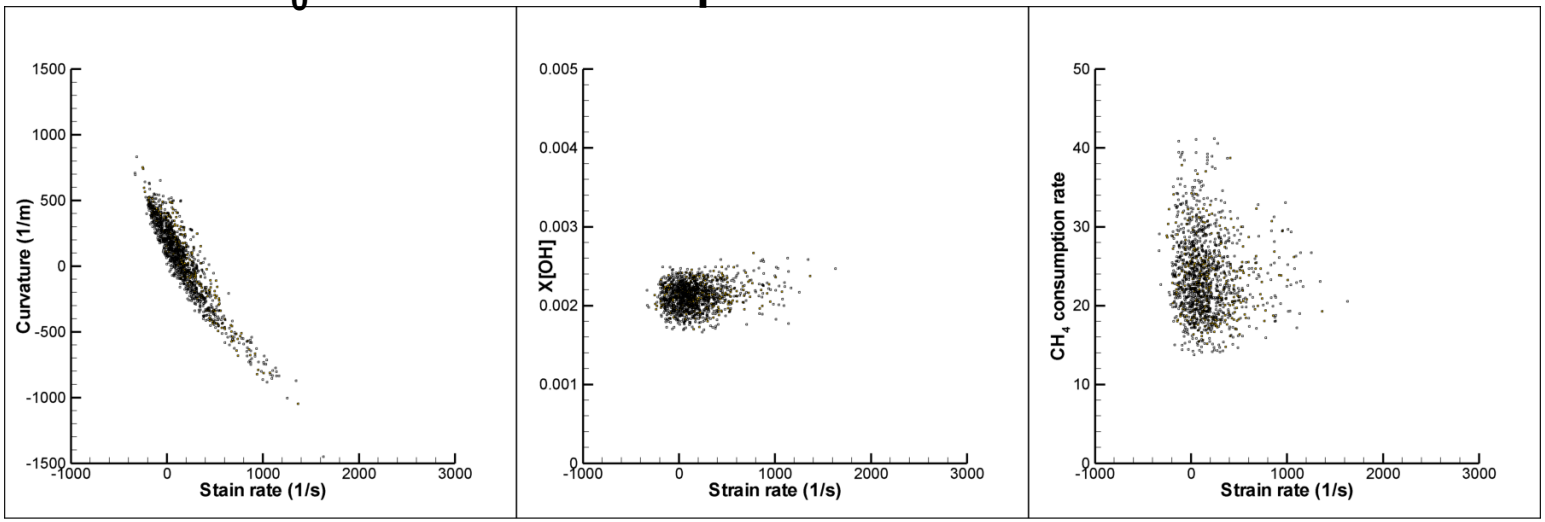
LaGrangian Flowpath Analysis of LMC Data



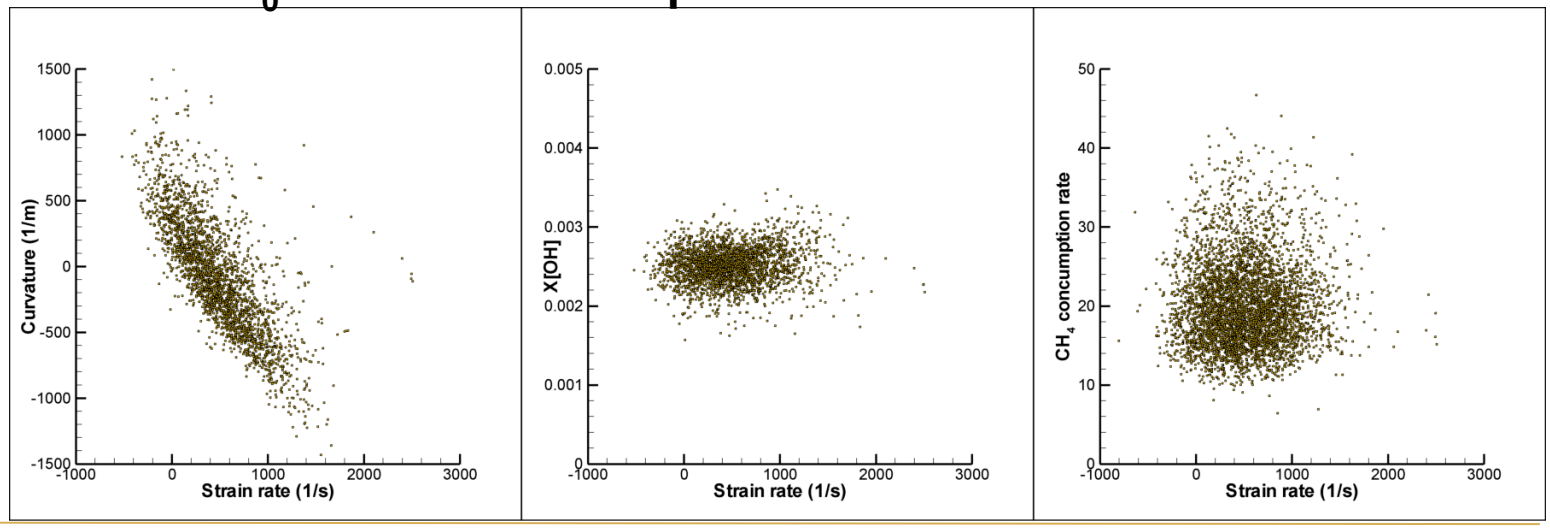
- Extract scalar and flow properties on flow traces through the flame front
  - 7000+ traces extracted in the central region r < 2 cm
  - Multi-species, scalar, and dynamic properties expressed in terms of space and time ($0.0001 < \Delta t < 0.00025$ sec)
- Facilitate analyses conditioned on progress variable, c, and local flame shape i.e. concave, flat, and convex

Strain rate effects on curvature, OH, and, CH_4 consumption consistent with increase turbulence

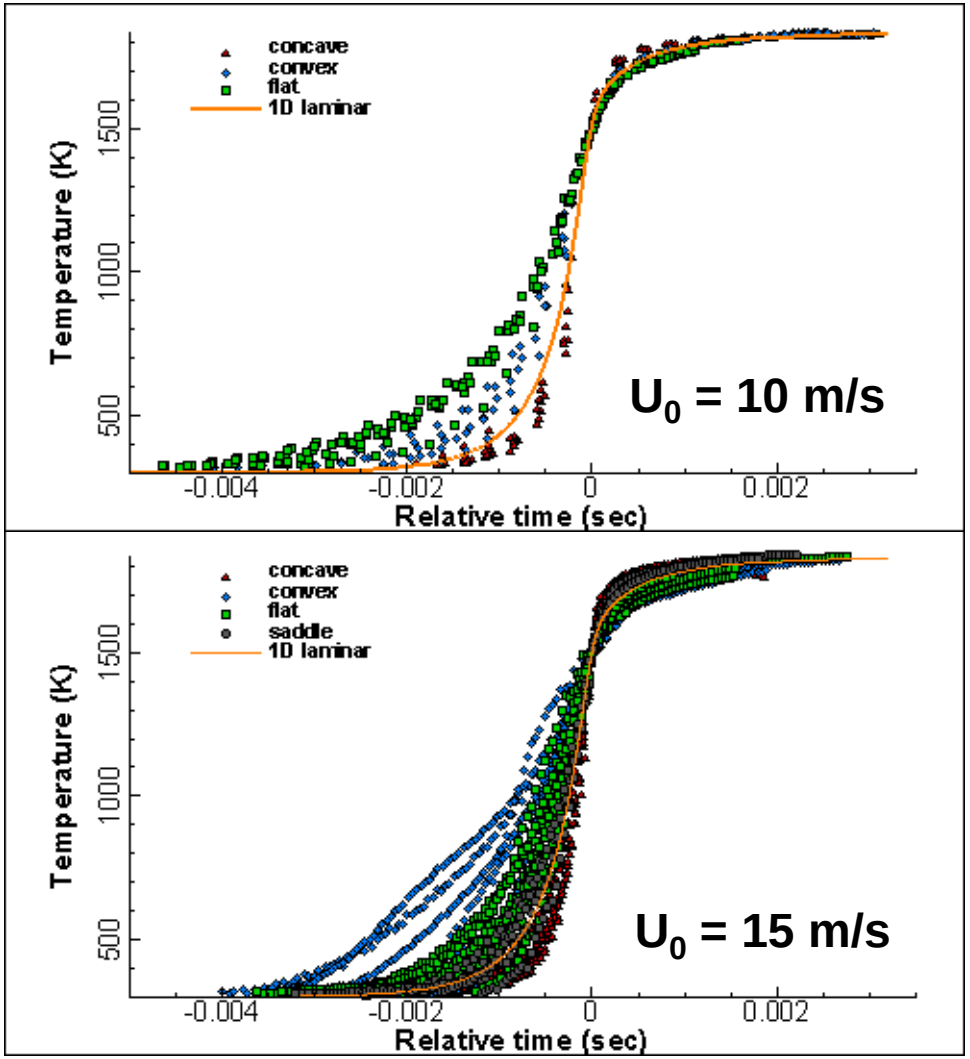
U_0 = 10 m/s scatter plots conditioned at c = 0.8



U_0 = 15 m/s scatter plots conditioned at c = 0.8



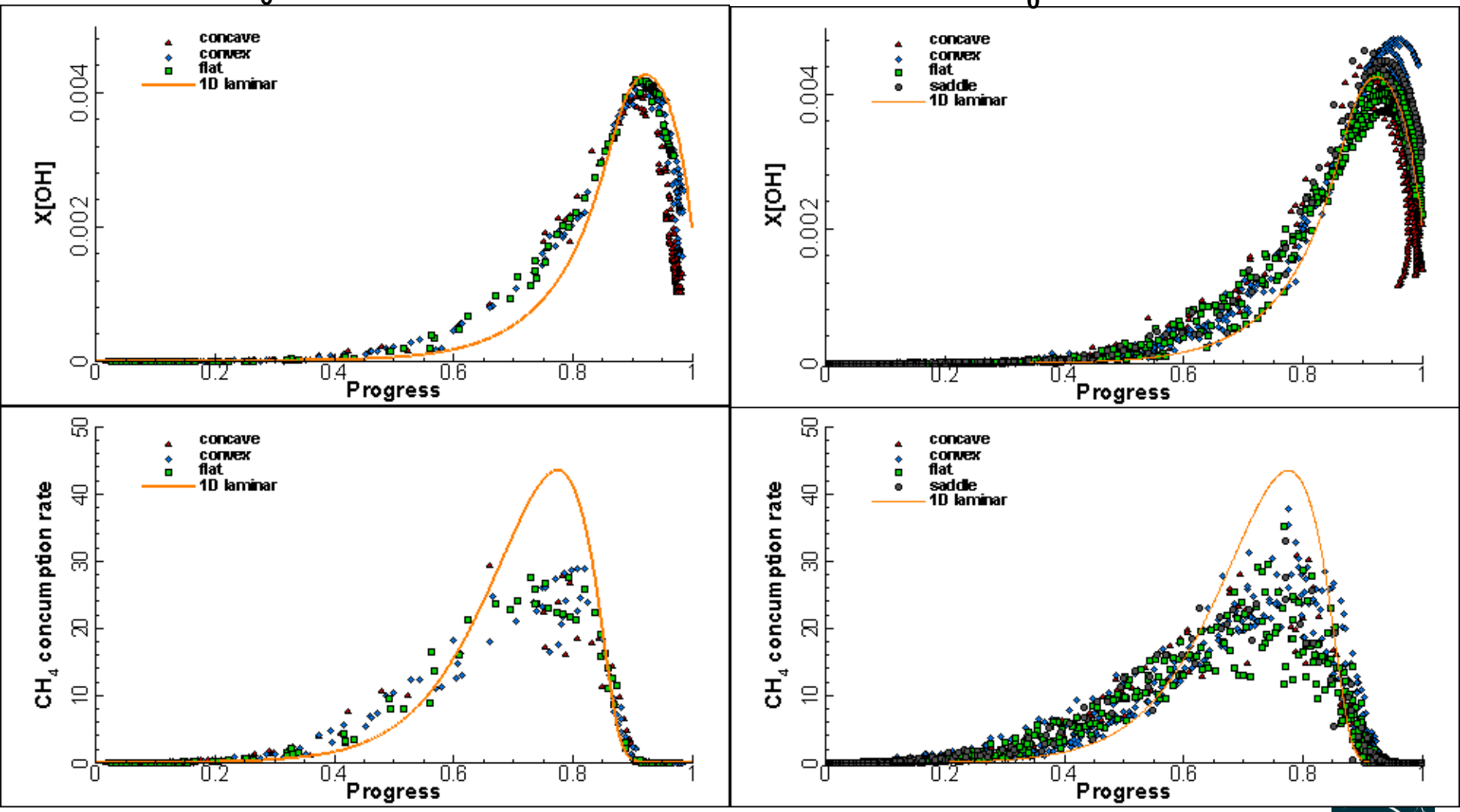
Comparison with 1D Flame Calculation Shows Turbulence Affecting the Preheat Zone



Invariant Peak OH Concentration Consistent with Wrinkled Flamelet Model

U_0 = 10 m/s

U_0 = 15 m/s



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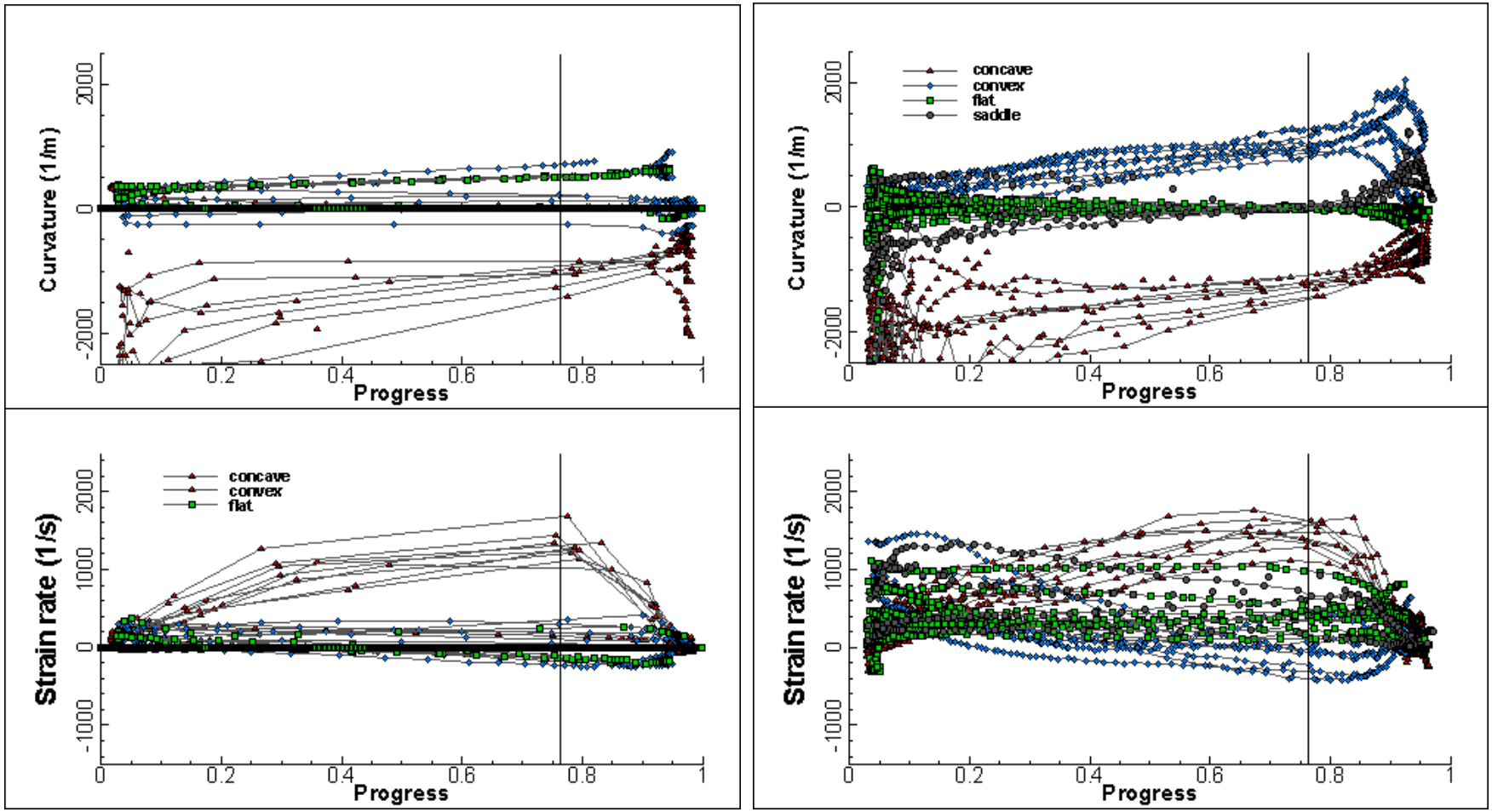
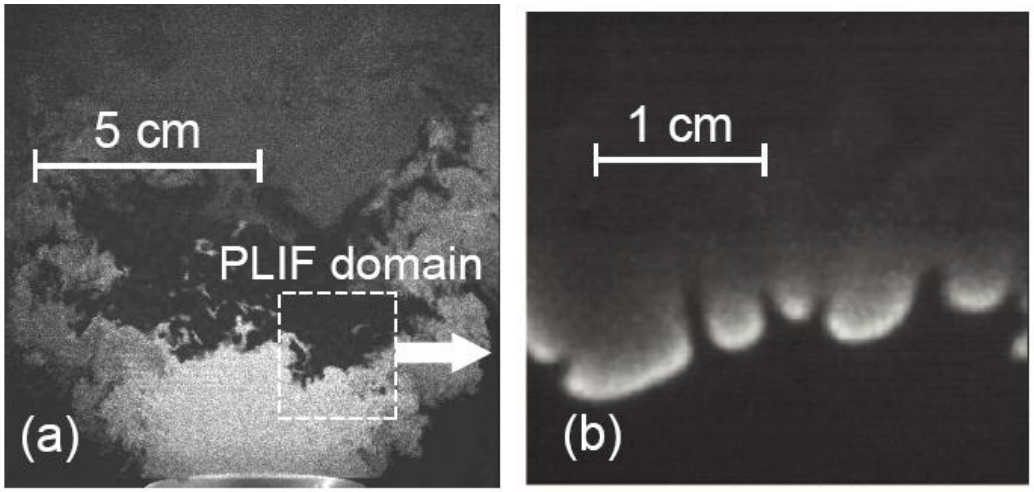
Significant Changes in Curvature and Strain Rate Illustrate Dynamic Nature of the Wrinkled Flamelets

U_0 = 10 m/s | **U_0 = 15 m/s**



Developing Analyses to Characterize H_2 Turbulent Flames



- Flame front analysis
  - Cross-correlation of local flame curvature with OH concentrations from PLIF
  - Cross-correlation of local flame curvature, OH & NO_x concentrations, and local heat release from AMR-DNS
- Flowpath analysis
  - Compare with 1-D calculation
  - Examine dynamic changes through concave and convex regions
- Relate H_2 flame front structures to the turbulent displacement flame speed
- Quantify the extend of thermal/diffusive instability effects
- Suggest appropriate flame models for H_2

Activities for FY11

- **Hardware Developments**
  - Design of LSI cluster for a silo-combustor
  - Develop conceptual fuel injection scheme for HHF
  - Laboratory experiments on LSI to LSI interaction
  - Develop engineering guidelines for H_2 LSI
- **3-fuel Gas Turbine**
  - Define operating range and fuel specifications
  - Conceptual architecture of the full-scale combustor
  - Propose engine-ready combustor design
- **Core technology support research**
  - Measure turbulent displacement flame speeds
  - Characterize structures of lean premixed H_2 flames
  - Publish results on the oscillation characteristics of LSI