Low-Swirl Burner for Fuel-Flexible Gas Turbines in Near-Zero Emissions Clean Coal Power Plants

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- **LBNL – Computational Science Div.**
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  - Pete Strakey & Todd Sidwell
- **Siemens Energy Inc.**
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- **Georgia Institute of Technology**
  - Tim Lieuwen & Bobby Noble
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- **Stanford University**
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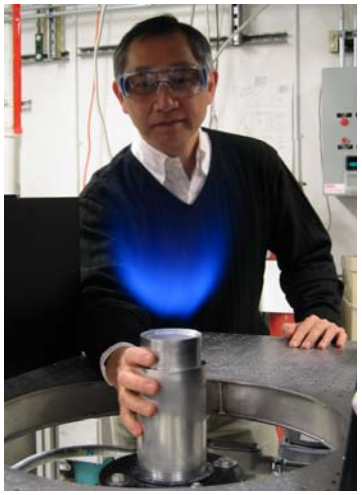
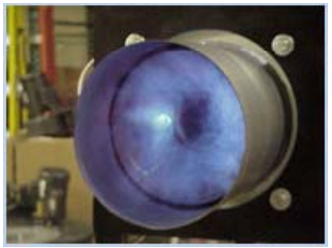
- **Hong Kong Polytechnic University**
  - C.K. Chan and Karl-Johan Nogenmyer

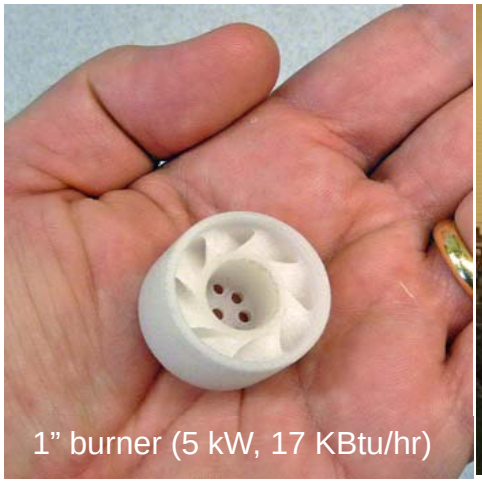
Background of Low-Swirl Burner

- **LSB operates on a non-recirculating flame stabilization method conceived at LBNL for DOE – BES basic research**
  - **Excellent laboratory tool for turbulent flame research**
    - **Detached flames approximates a locally normal premixed turbulent flame**
    - **Supports stable premixed flames under intense turbulence at ultra lean to rich stoichiometries**
    - **Basic principle obtained from experimental measurements**
      - **Exploits turbulent displacement flame speed, S_T - the most basic property of the premixed flames**
      - **Flame propagating in divergent flow –fundamentally different than the flame holding approach of conventional high-swirl burners**
      - **Not valid for non-premixed combustion**
    - **Adopted by researchers worldwide**
  - **Robust clean combustion technology**
    - **2 US patents**
    - **Basic understanding facilitated adaptation to practical systems**
    - **Commercialized for industrial burners**
    - **Adapted to 80 kW to 7 MW gas turbines**
    - **Ongoing developments for residential and commercial heaters**

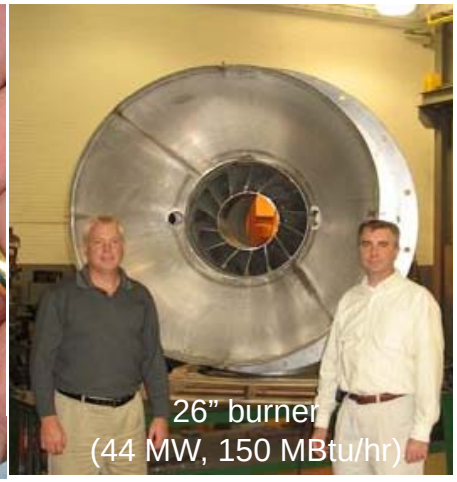


LSI for Solar's T70 utilizes the SoLoNOx swirler





1" burner (5 kW, 17 KBtu/hr)



26" burner (44 MW, 150 MBtu/hr)

LSB Uses a Patented Vane Swirler

- ≈30% of the premixture bypasses swirl annulus through a center tube
  - Unswirled bypass mitigates recirculation and promotes divergence
- Utilizes conventional vane designs
  - Flat blades for low velocity operation
  - Converted SoLoNOx to low-swirl injector (LSI)
- Swirler design is scalable
  - Engineering guidelines developed
  - Basic configuration and swirl number ($0.4 < S < 0.55$) independent of size
- Commercial LSB since 2003
  - Over 1000 units in operation 24/7
  - Low pressure drop design offering high turndown (up to 60:1 in lab tests)
  - Guarantee 4-7 ppm NO_x (@3%O_2)

DOE-FE 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 LSBs**
  - **Modify LSB 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 LSB combustors for the HHF gas turbines in IGCC**
  - **Participate in demonstration of LSB in utility-size gas turbines that meet the cost and performance targets of FE's Advanced Turbine Program**

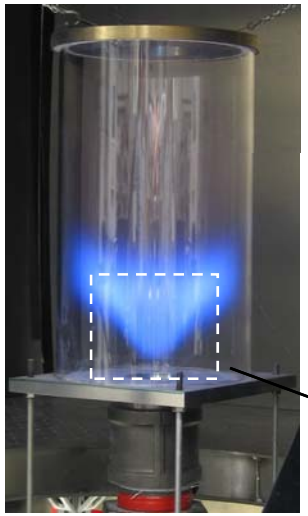
Technical Issues for Adapting LSB to H_2 Gas Turbines

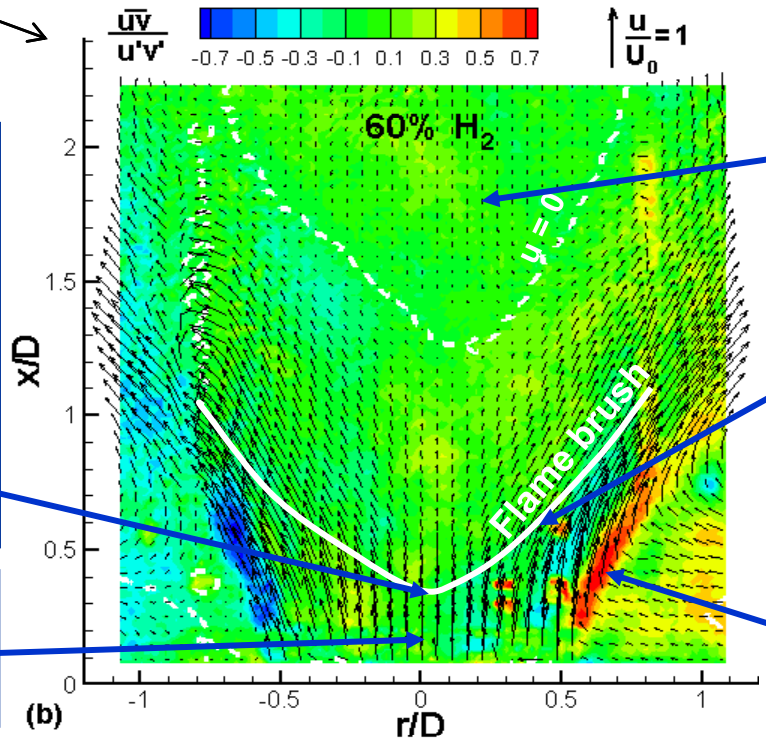
- **Scalability of the LSB to the size and power of utility gas turbines**
- **Fuel-flexibility of the LSB to operating with natural-gas, syngases, and HHF (3-fuel) without requiring significant hardware changes, moving parts, or elaborate controls**
- **Mitigating combustion dynamics and H_2 flame flashback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

Progress To Date

- **Milestones**
  - **Adapted LSB to existing gas turbine systems**
    - **Scaled LSB for natural gas F-class turbines (collaboration with Siemens Energy Inc.)**
  - **Demonstrated fuel-flexible capability of the LSB swirler design**
    - **No adjustment required for pure H_2 operation**
    - **Operated with NG and H_2 at simulated gas turbine conditions and show the potential to met DOE Advanced Turbine Program's aggressive 2 ppm (@15%O_2) NO_x target (collaboration with NETL - Cheng et. al. Proc. Comb. Inst. 2008)**
    - **Operated with syngases at gas turbine conditions (collaboration with Georgia Tech - Littlejohn et. al. JEGP, 2009)**
  - **Developed an analytic model to illustrate fuel effects on flame behavior**
    - **Upstream shift of H_2 flame positions due to higher correlation constant of the turbulent displacement flame speed (Cheng et. al, JEPG 2008)**

Features of the LSB Flowfield Inside SimVal Combustor





Axial velocity at the leading edge of the flame brush defines the local turbulent displacement flame speed, S_T, that correlates linearly with, u', the local turbulent fluctuation

Near field divergence below flame brush is self-similar

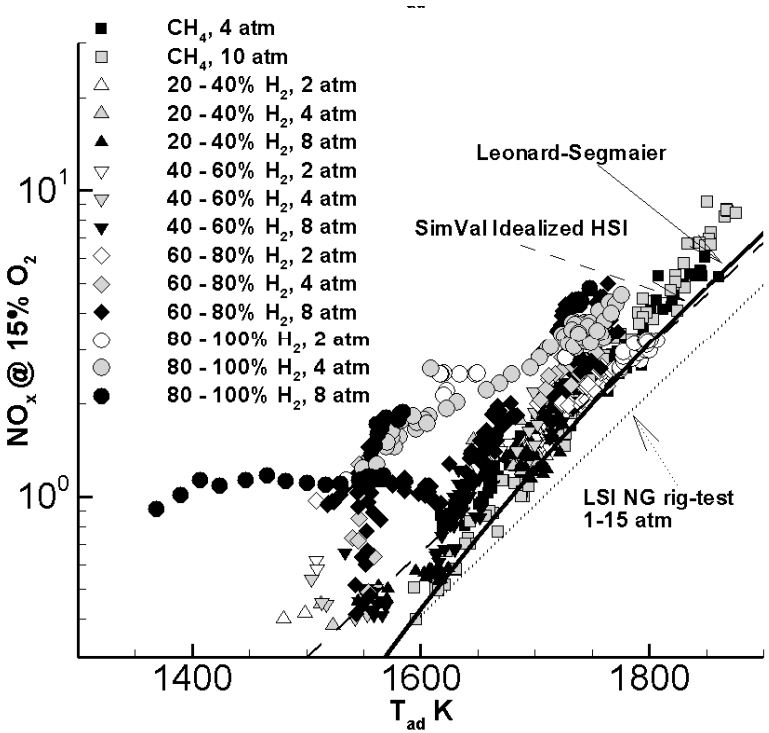
Size and strength of the central downstream recirculation zone vary with U_0 and ϕ

Flame brush position invariant with U_0 and ϕ

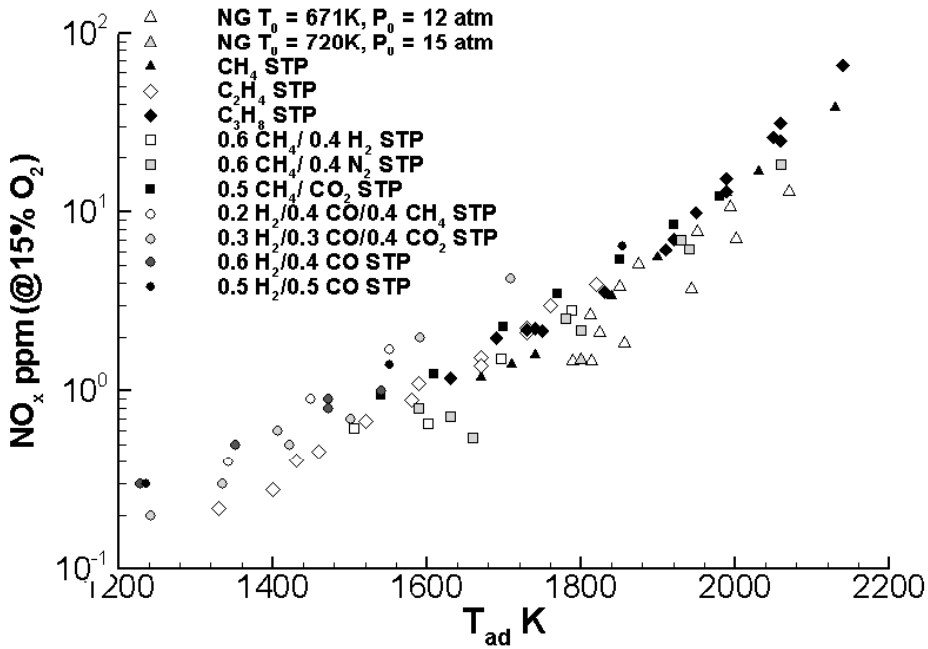
Intense turbulence confines to the outer shear layer and corner recirculation zone

NO_x Emissions of LSB

- **Hydrocarbons and syngases NO_x has an overall log-linear trend with T_{ad} that is independent of LSB configuration and initial conditions**
- **H_2 flame shows a NO_x "floor" of 1 ppm**



NETL SimVal

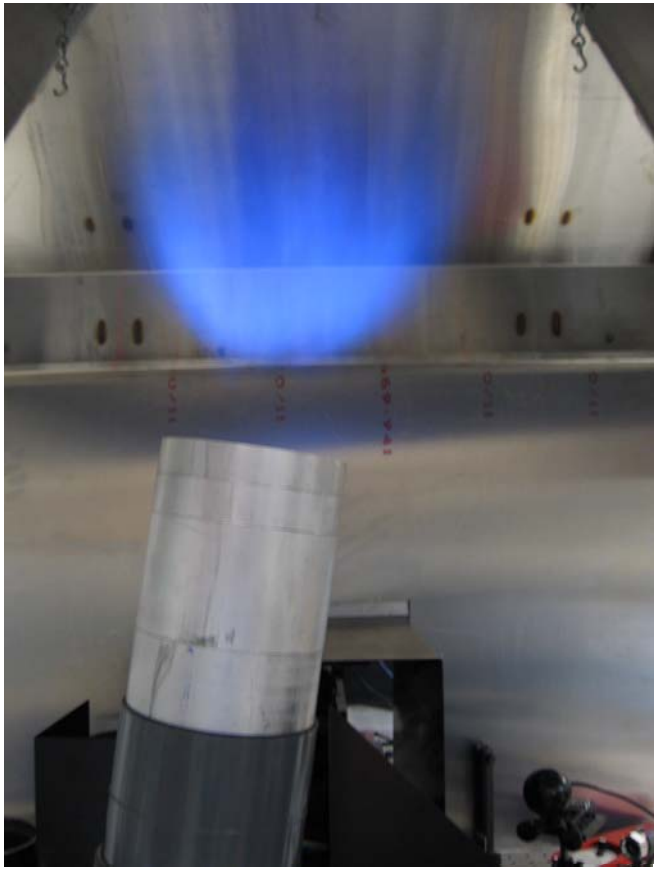


Solar Turbine, LBNL

Current Focuses

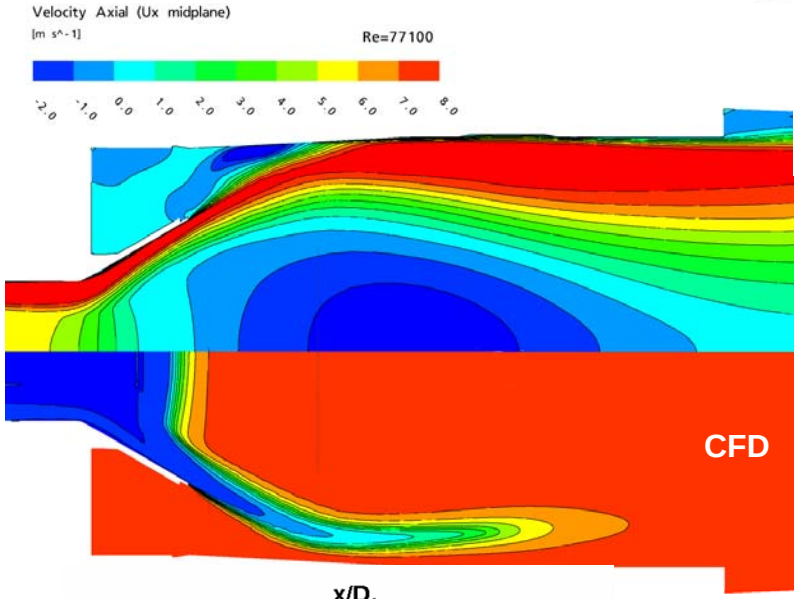
- **Optimization to attain low single digit NO_x for natural gas**
  - **Support CFD development to predict LSB flame behavior and flowfield in combustor**
  - **Investigate instability and acoustics characteristics of LSB flames**
- **Modification of LSB nozzle to address H_2 specific issue**
  - **Integrate a divergent section to mitigate influences from corner recirculation**
- **Conceptual study of a 3-fuel (natural gas, syngas and HHF) capable LSB system**
  - **Estimate the basic requirement of the fuel handling and injection system and the impact on gas turbine operation and control**
- **Conduct core technology support research**
  - **Collaborate with DNS developers to characterize the effects of thermal/diffusive instability on the basic structure of H_2 flames and their implication to models and NO_x emissions**

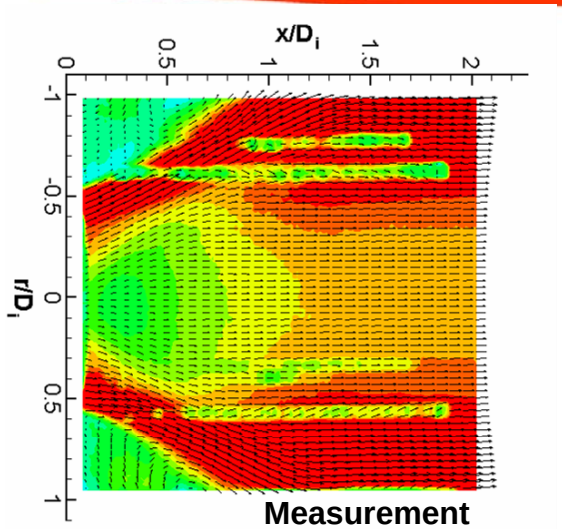
Scaled LSB for Siemens' F-class Engine



- **Configured LSB for the combustor**
  - **Size and form of LSB compatible with existing burner**
    - **Down-selected swirler designs by test firing with resin models at low velocities < 10 m/s**
    - **Optimized flame position by tuning the swirl number**
    - **Reduced shear stresses generated by vanes and center channel wall**
- **LSB prototype evaluated at simulated conditions of F-class engines**
  - **LSB light-off, loading, and responses to control show some advantage over existing hardware**
  - **NO_x emissions within expectations**
  - **Oscillations characteristics needs further studies**

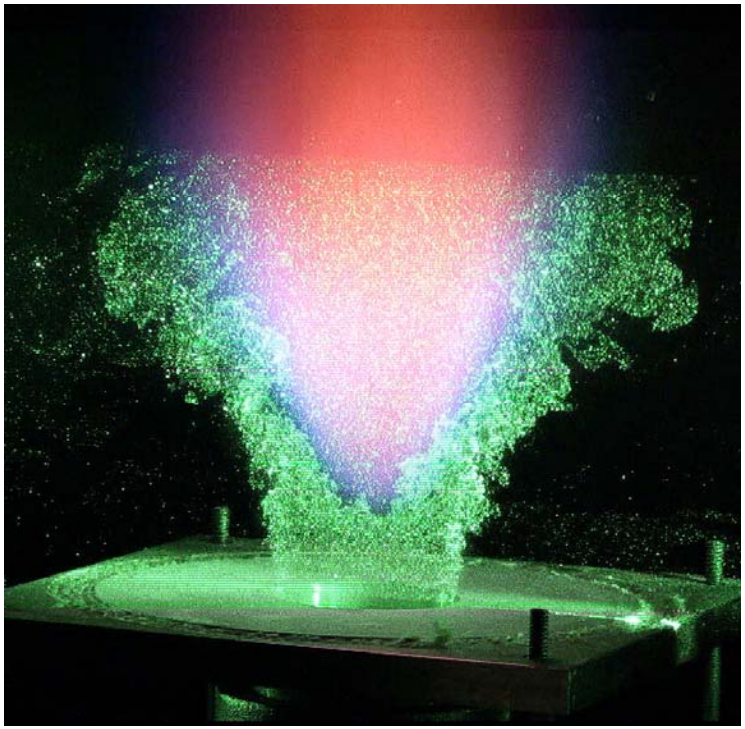
Lack of Computational Design Tools for LSB can be a Drawback for Development





- **Computational Fluid Dynamics (CFD) is needed to**
  - **evaluate LSB interaction with the combustor**
  - **predict flame response to hardware change**
  - **identify origins of NO_x and flame instabilities**
- **All Reynolds Averaged Navier-Stokes (RANS) CFD codes perform poorly for LSB**
  - **Over-predict the strength of the downstream recirculation zone**
  - **Show burning in outer shear layer for CH_4 flames**
  - **Main issue**
    - **RANS turbulent models needs to be re-calibrated for low-swirl flows**
- **Large eddy simulations (LES) at NETL, GIT, and Stanford produced more promising results**
  - **Higher order commercial LES codes still under-development**
- **RANS and LES need better combustion models for H_2**

Laboratory Studies for CFD Validation

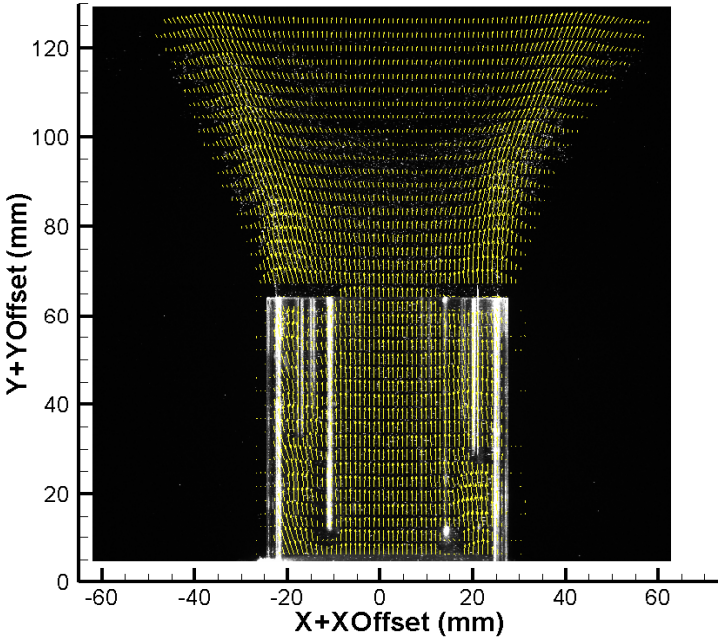


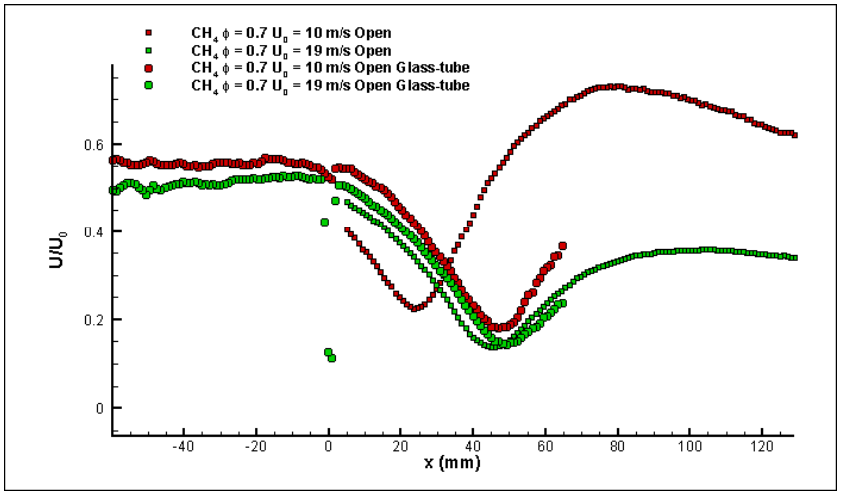
- Developed benchmark swirler for sharing with CFD developers
- Initiated a coordinated experimental, numerical, and analytical study to address computational and modeling problems with participants at LBNL, NETL, SEI, and universities
- Measure flowfields inside and outside the LSB
- Characterize enclosed LSB flowfields to verify CFD results

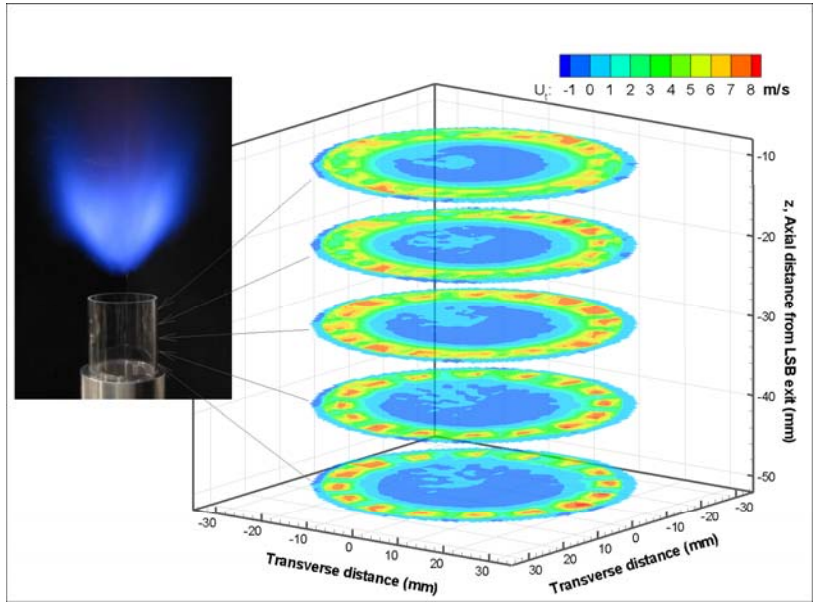
Benchmark LSB Swirler for Experiments and Computations

- 16 thick vanes at 37° discharge angle
- Fabricated in several sizes for
  - NETL's SimVal facility designated as "SV7"
  - GIT's high pressure combustion chamber
  - U of Iowa's high pressure acoustics chamber
- "SV7" for next round of NETL CH_4/H_2 tests at simulated gas turbine conditions
  - 37 holes opened of 3.66 mm diameter in a hexagonal pattern
  - Center hole blocked to simulate pilot
  - Baseline PIV data at atmospheric conditions obtained at LBNL

PIV Data Inside LSB for CFD Validation







- **Centerline profiles show the flowfield of SV7 is fully developed at U_0 > 10 m/s**
- **Cross-plane data show the degree of interaction between the swirled and the unswirled flows**

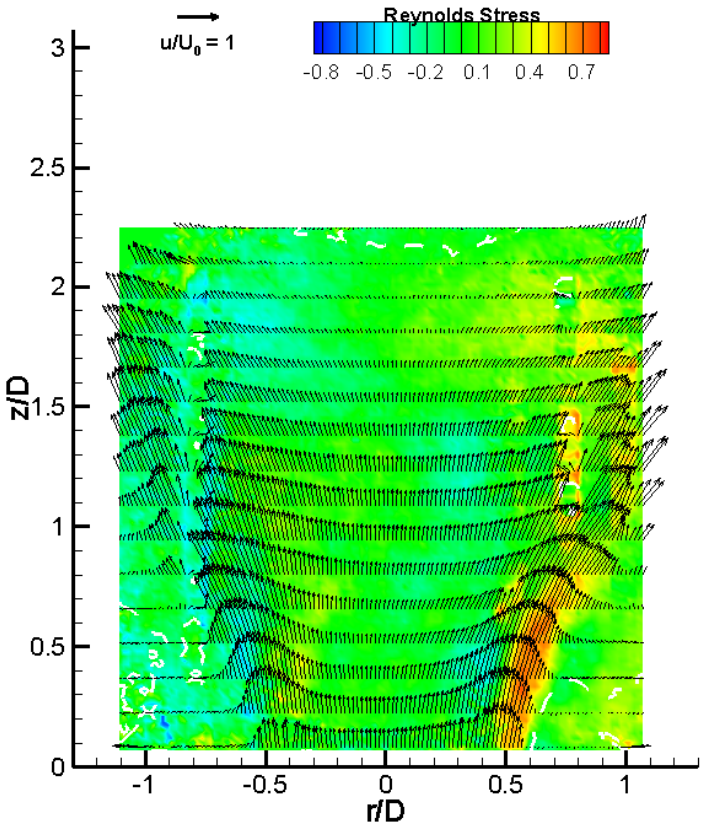
LSB in SimVal Enclosure Shows Limitations of an Idealized Combustor Configuration

- **Planar combustor dump-plane necessary for laser access but not ideal for LSB operation**
  - **Corner recirculation promotes H_2 burning in outer shear layer (Cheng et. al. Proc. Comb. Inst, 2008) and contributes to significant flame noise**
- **Divergent quarl reduces flame noise and mitigates H_2 flame attachment but obscures laser access**
  - **Preferred configuration for engine adaptation but critical part of the flame is inaccessible for detailed studies**

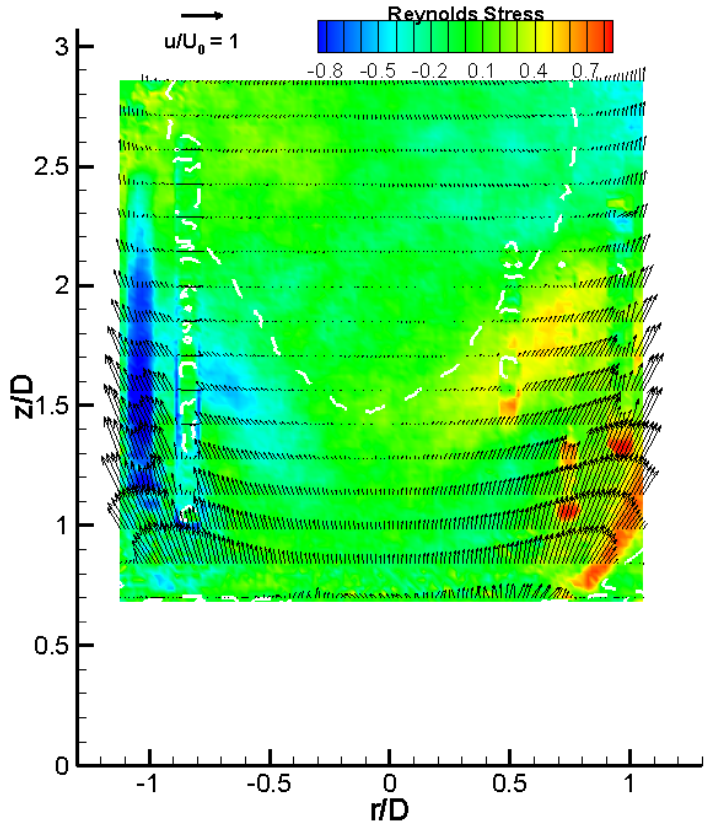
2 Sets of PIV Data : With and Without Quarl

- **Over 20 CH_4, H_2, CH_4/H_2 flames investigated**
  - **H_2 flame conditions focus on those that do not burn in the outer shear layer**

Without quarl



With quarl



2D velocity vectors for a 0.9 H_2/ 0.1 CH_4 flames at ϕ = 0.35 and U_0 = 15 m/s show that the quarl affects the size and location of the downstream central recirculation zone

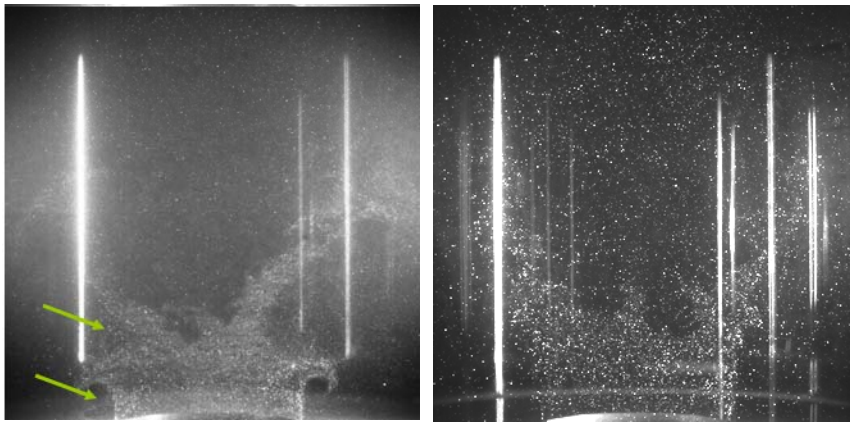
LSB Velocity Data Available for CFD

- **Focus on two swirler configurations and share data with CFD developers**

Burner	ID	Vanes	Enclosure	Fuels	U_0 (m/s)	T, P	CFD
LBNL LSB	5.08 cm	8 curve thin blades	Open	CH_4	5 – 15	STP	Stanford LES
Darmstadt/ Lund/LBNL LSB	5.00 cm	8 curve thin blades	Open,	CH_4, H_2	10 - 19	STP	Lund LES LBNL LM-DNS
Solar LSI	6.35 cm	16 constant radius thin blades	Open, 20 cm, and 15.5 cm cylinders	CH_4, CH_4/H_2, syngas, H_2	5 – 22	STP	Solar/CSE RANS
SimVal LSB-1	5.7 cm	16 constant radius thin blades	18 cm cylinder	CH_4, CH_4/H_2, H_2	18	STP	NETL RANS
SimVal SV7	5.7 cm	16 thick blades	Open, 18 cm cylinder	H_2, CH_4, 0.9 H_2/0.1 CH_4	10, 15, 18	STP	Stanford LES
GIT/Iowa LSB	3.81 cm	16 thick blades	Open, 7.62 cm cylinder	CH_4	10 – 30	STP, T = 500K, P=4atm	GIT LES, Siemens RANS

Characterizing the Effects of the Divergent Quarl on Flame Noise

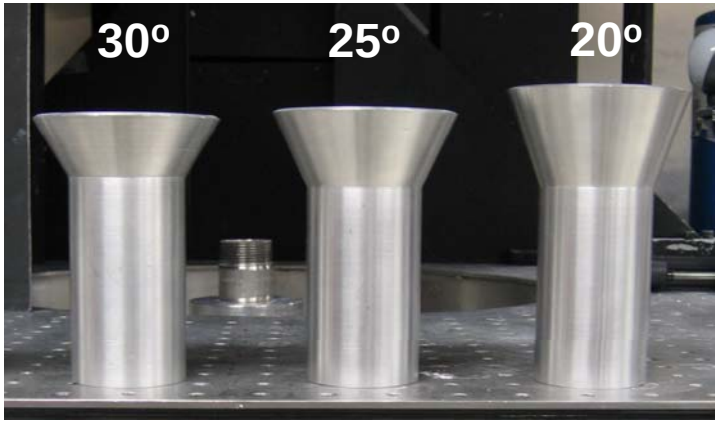
Divergent quarl prevents the formation of large vortices in the outer shear layer that causes very high levels of flame noise

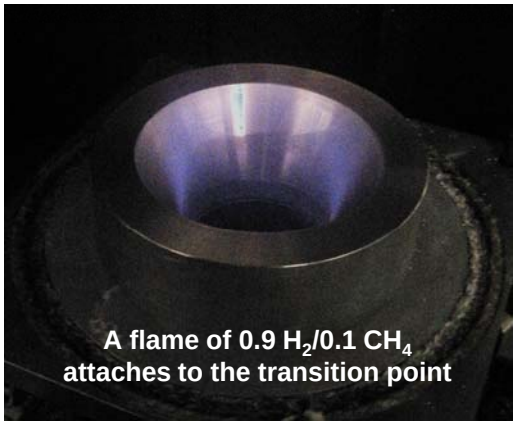


In SimVal combustor with sudden expansion dump-plane the loud CH_4/air flame, at $\phi = 0.7$ and $U_0 = 18$ m/s (left) generated large roll-up vortices in the outer shear layer that are not present in the much quieter flame at $U_0 = 10$ m/s (right)

- **Goal**
  - **Gain some insights on acoustics and combustion dynamics characteristics of LSB**
- **Approach**
  - **Collaborate with SEI to design a setup to measure and analyze pressure fluctuations at various positions along the flow supply line and in the combustor**
  - **Investigate CH_4 and H_2 flames with and without the divergent quarl in enclosures of different sizes and lengths**
- **Progress**
  - **Preliminary data obtained for CH_4 flames in SimVal combustion chamber with and without quarl for the development of analytical methods**

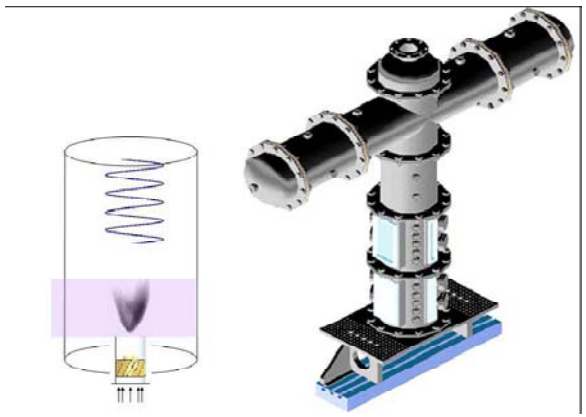
LSBs with Divergent Nozzles

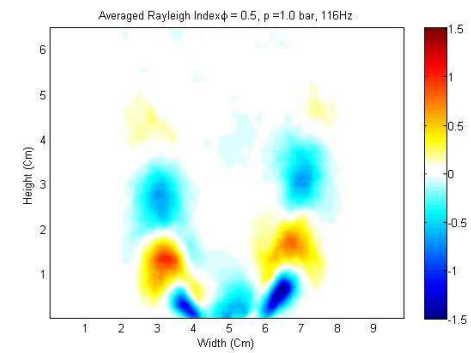


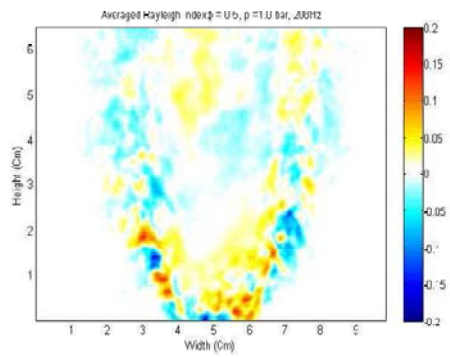


- **Divergent nozzle is a standard feature of commercial LSB that is essential for H_2 operation in a gas turbine**
- **Investigated nozzles with 20° to 30° half-angle**
  - **No observable dependency of lean blow-off on half-angle**
  - **PIV data show slight increase in central recirculation strength with decreasing half-angle**
- **H_2 flames anchors behind the sharp transition point between the straight and the divergent sections**
  - **Flow separation behind the transition point produces sufficiently high shear turbulence to anchor the faster burning H_2 flame**
- **Fabricating divergent nozzle with smooth transition to mitigate H_2 flame attachment**
  - **To be evaluated at simulated gas turbine conditions at UCI**

U. of Iowa Investigating Fuel and Pressure Effects on LSB Flame Stability







118 Hz **208 Hz**

Local Rayleigh Index

- **Previous study used phase-resolved OH-PLIF on CH_4 flames**
  - **flame instability confined to outer shear region**
- **Planned studies on CH_4/H_2 flames using a benchmark 1.5” LSB**
  - **Characterize pressure induced changes between 1 and 3 bar of 100% CH_4 to 100% H_2 flames with and without divergent nozzle**
  - **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**

Feasibility Study of a 3-Fuel Low-Swirl Injector (LSI)

- **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
    - Natural gas as a startup and backup fuel, syngas as a transition fuel, high hydrogen fuel (HHF) for baseload
  - Estimate the impact on turbine operation
- **Preliminary results available in a draft report**
  - Significant differences in Wobbe indices of natural gas, syngases and HHF requires at least two parallel main fuel circuits
  - Central pilot may be needed to ensure operational flexibility
  - Refinement of the LSI and a detailed assessment of the entire combustion system to be conducted at a later stage after a candidate engine for prototype development is selected

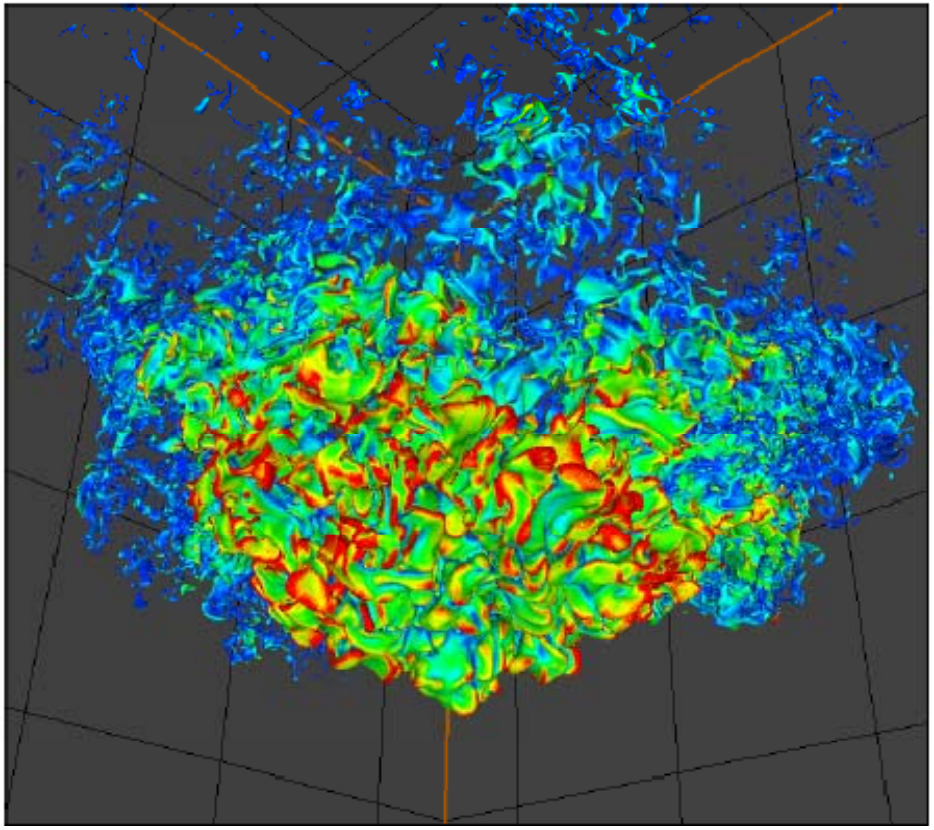
Issues and Potential Challenges of a 3-Fuel LSI Combustion System

- **Issues**
  - Combustor cooling – changes in temperature distribution
  - Fuel injection length – auto-ignition risk vs. mix. homogeneity
  - Fuel spokes design – fuel pressure consideration
  - Combustor volume – residence time vs NO_x
  - Combustor acoustic oscillations – unknown LSB acoustics
  - Increase turbine flow – risk of compressor surge
  - Optimum syngas compositions – unknown cost/benefit of reducing fuel variability
- **Next step**
  - Seek a contractor to review and critique the analysis and to develop and fabricate a conceptual prototypes for rig-tests

Symbiotic Experimental/Numerical Studies to Develop Lean Premixed Turbulent H_2 Flame Models

- **Lean H_2 laminar flames, the foundation for turbulent flame models, have not been well characterized**
  - **Lean H_2/air premixed flames are inherently unstable due to preferential diffusion of heat and mass, i.e. the thermo-diffusive instability effects**
  - **Instability hampers laminar flame speed, S_L, measurements**
    - **Bomb experiments requires corrections to obtain un-stretched laminar flame speed**
    - **Counterflow burner imparts large positive stresses to suppress thermo-diffusive instability**
  - **Chemical kinetics schemes for lean H_2/air flames under predict S_L**
    - **Huge scatter in predicted S_L of lean H_2 flames**
    - **Rate constants for third body reactions and molecular transport coefficients need further studies**
- **Reliable H_2 turbulent flame models for CFD is lacking**
- **LSB ideal for H_2 studies**
  - **Exploit unique capability of LSB to obtain experimental data for model validation**
    - **Most laboratory burners cannot support turbulent H_2 flames due to flashback occurring when H_2 > 25%**

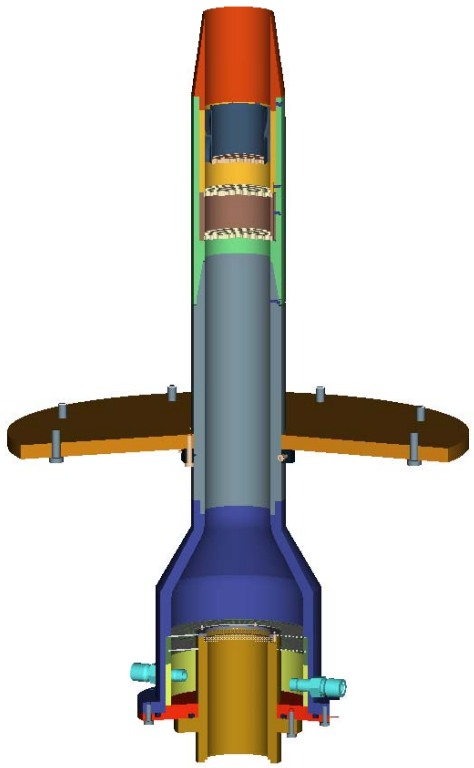
LBNL Mathematicians are Experts in Large-Domain Direct Numerical Simulations



Local heat release rate of H_2 flames can be 3.5 times higher than the heat release rate based on global stoichiometry

- **Numerical results can provide useful insights to elucidate underlying physics**
  - **Complex 3D flame structures cannot be captured by the best available laser diagnostics**
- **John Bell's Center for Computational Science and Engineering (CCSE) at LBNL specializes in large domain 25 cm^3 3D time-dependent direct numerical simulation (DNS) of turbulent premixed flames**
  - **Solution of low Mach number equations with full chemistry kinetic scheme using adaptive mesh refinement (AMR) method**
  - **Wealth of information to be gained from analysis of the AMR-DNS results**
- **Recent award of 3.4 x 10^6 hr on supercomputers to focus on LSB H_2 combustion problems relevant to IGCC**

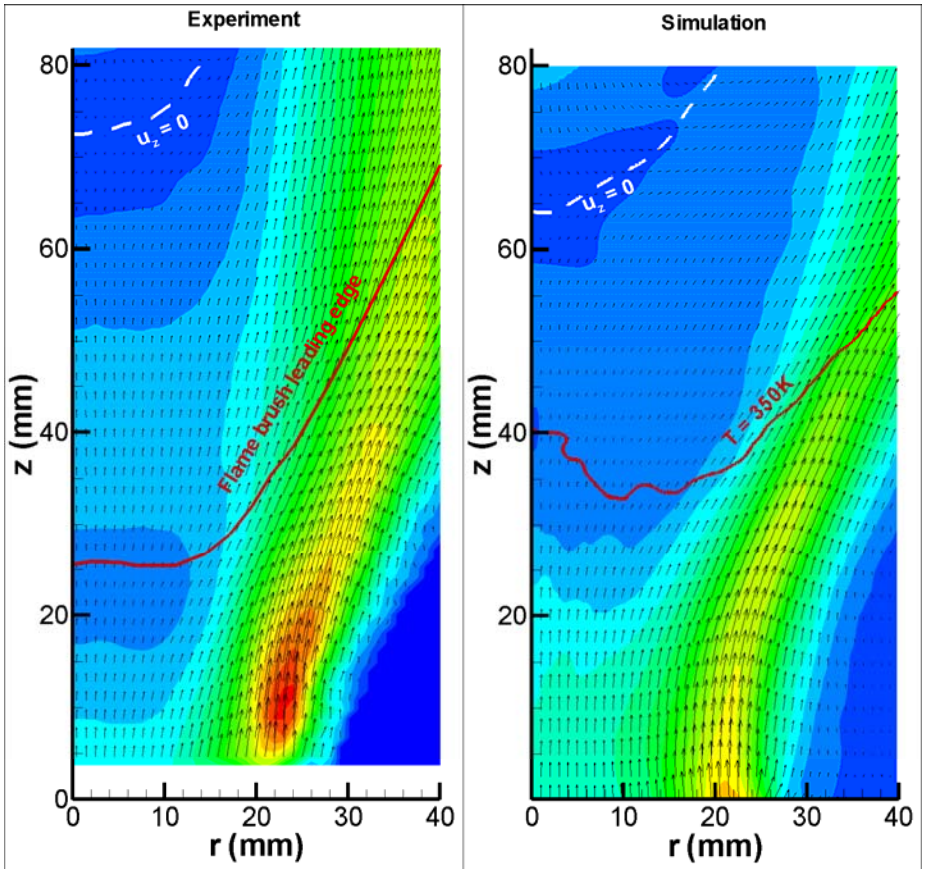
Darmstadt/Lund/LBNL LSB for OH-PLIF, PIV & AMR-DNS of CH_4 and H_2 Flames



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

- **5 cm i.d. burner with co-flow specially designed to facility high-power laser diagnostics**
  - Standardized burner configuration to facilitate data exchange and sharing
- **OH-PLIF and PIV measurements of 15 CH_4, CH_4/H_2 & H_2 flames at $3 < U_0 < 18$ m/s**
- **AMR-DNS of 2 CH_4 flames, 2 H_2 flames & 5 CH_4/H_2 flames at 10 and 15 m/s**
- **Experimental and simulation results to be analyzed the same way**
  - 2D information on mean flame statistics (Σ, S_T, etc.), and flame wrinkle geometry
  - 3D analysis of DNS local flame structures to support interpretation of 2D information from experiments
- **3 publications planned**

Validation of AMR-DNS



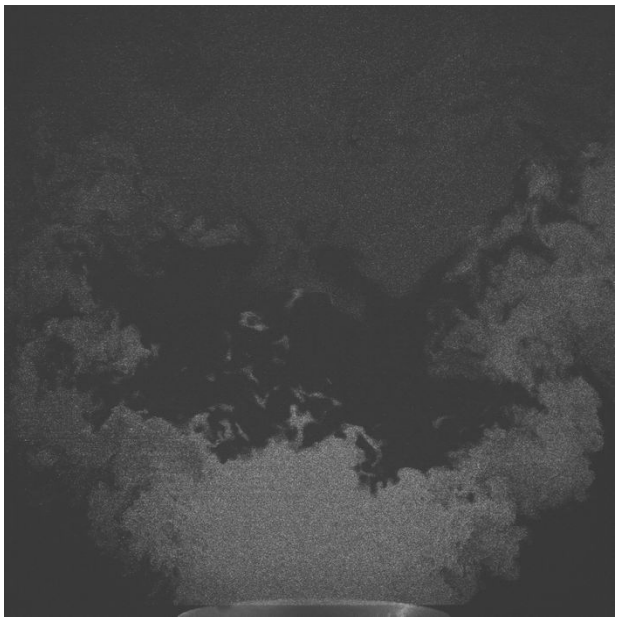
Measured and simulated flowfields of a CH_4/air flame at ϕ = 0.7 and U_0=15 m/s

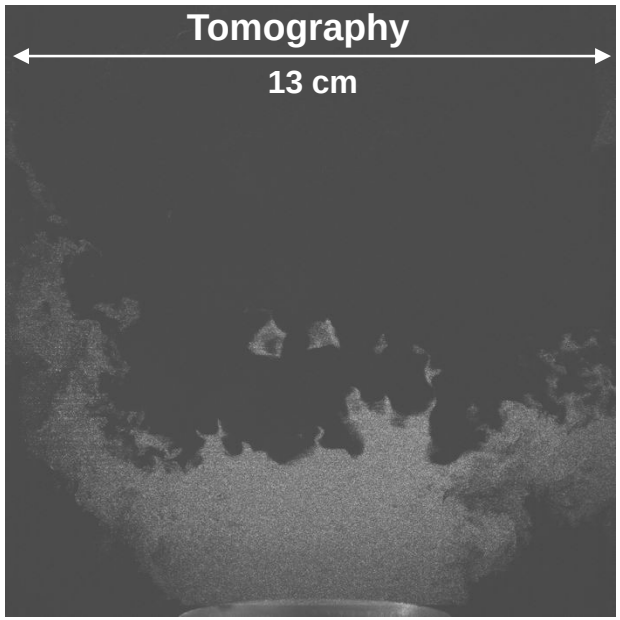
- **AMR-DNS captures the salient features of the flowfied**
  - **Distribution of the velocity vectors, the mean flame location and the formation of the weak recirculation downstream with increasing U_0 are in good agreement**
  - **Small discrepancies in the velocity magnitude attributed to the use of an azimuthally uniform inflow velocity**
  - **Mean velocity statistics less stable due to the very short duration of the simulated physical time domain**
- **Agreement between the experiments and the simulation is very encouraging**
- **Simulated results are sufficiently stable for detailed analysis of the local flame front properties associated with the shorter time scales**
  - **Adequate for meaningful analyses of local flame wrinkle scales and thermal/diffusive effects of H_2 flames**

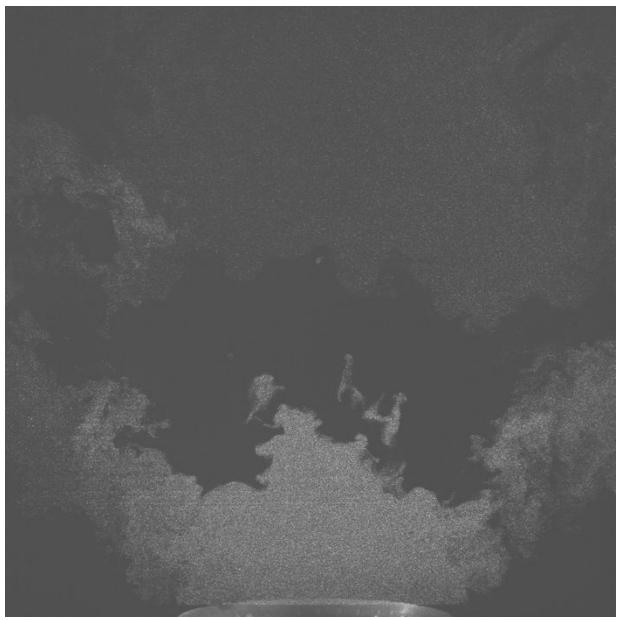
OH-PLIF of CH_4, C_3H_8 & H_2 Flames Show Thermal/Diffusive Effects on Flame Structures

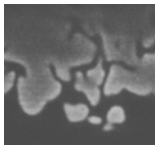
- **Thermal/diffusive unstable H_2 flames generate finer flame wrinkles with distinct topology and gaps in OH concentrations**

H_2 , ϕ = 0.3, Le = 0.33 | **CH_4, ϕ = 0.8, Le ≈ 1** | **C_3H_8, ϕ = 0.75, Le = 1.85**



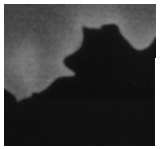


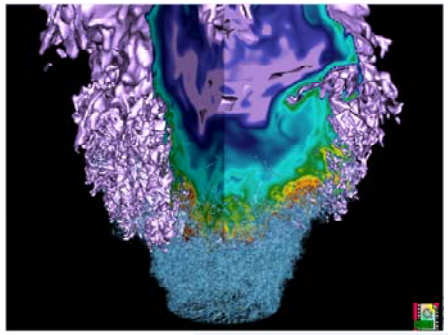




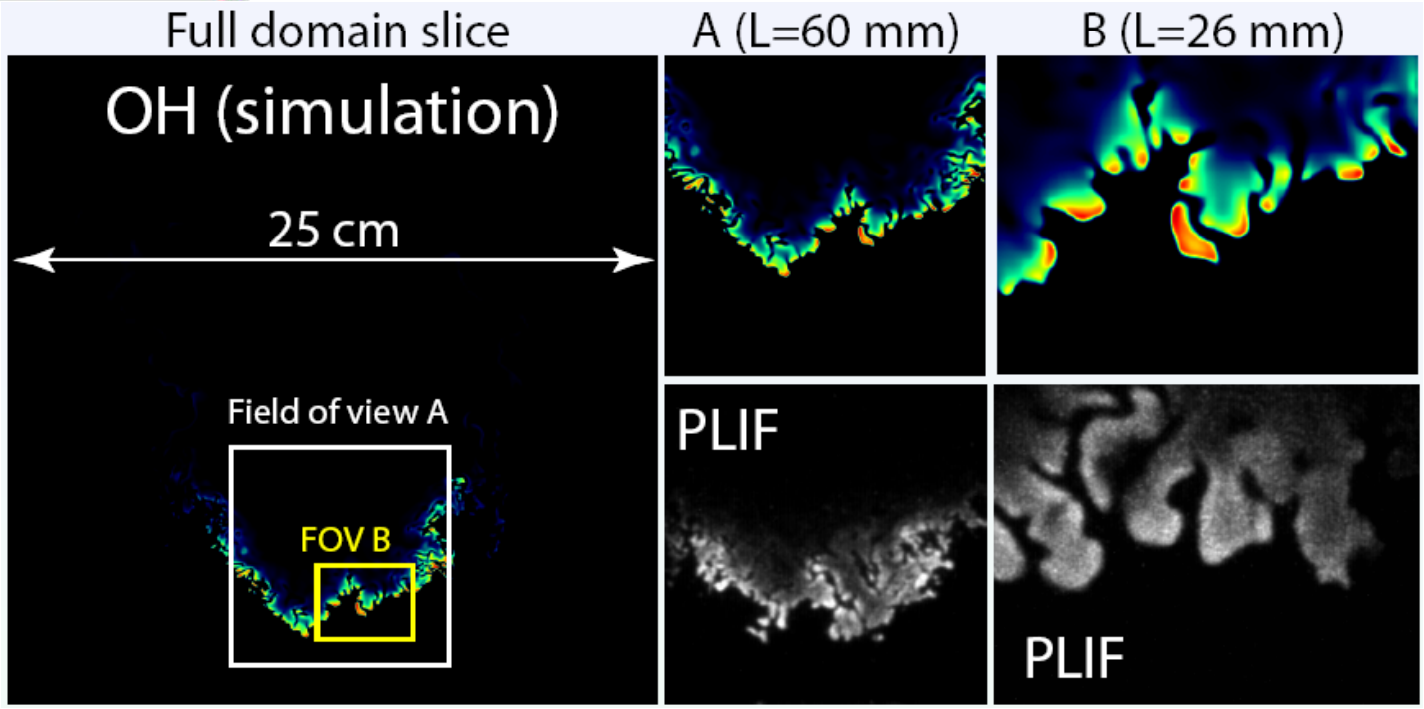
OH-PLIF

3 cm



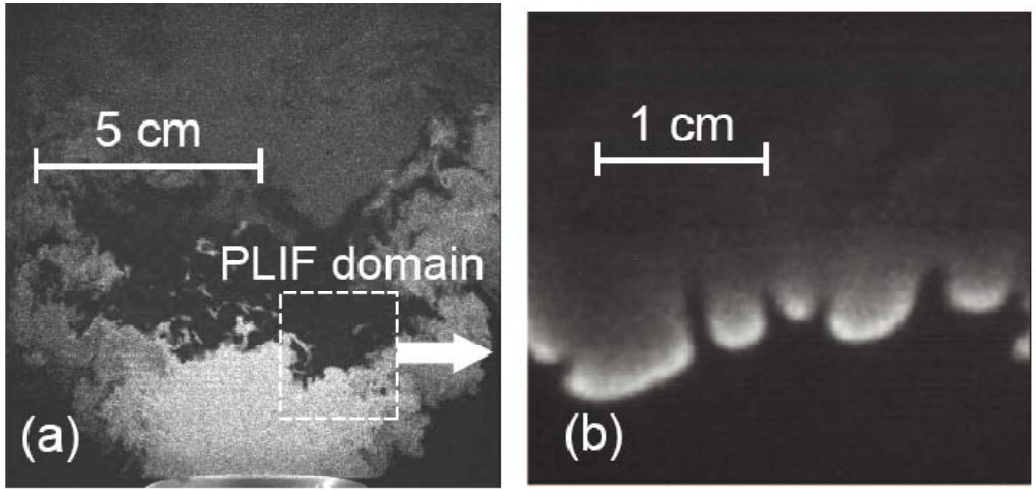


AMR-DNS Elucidates Local Structures of H_2 Flames



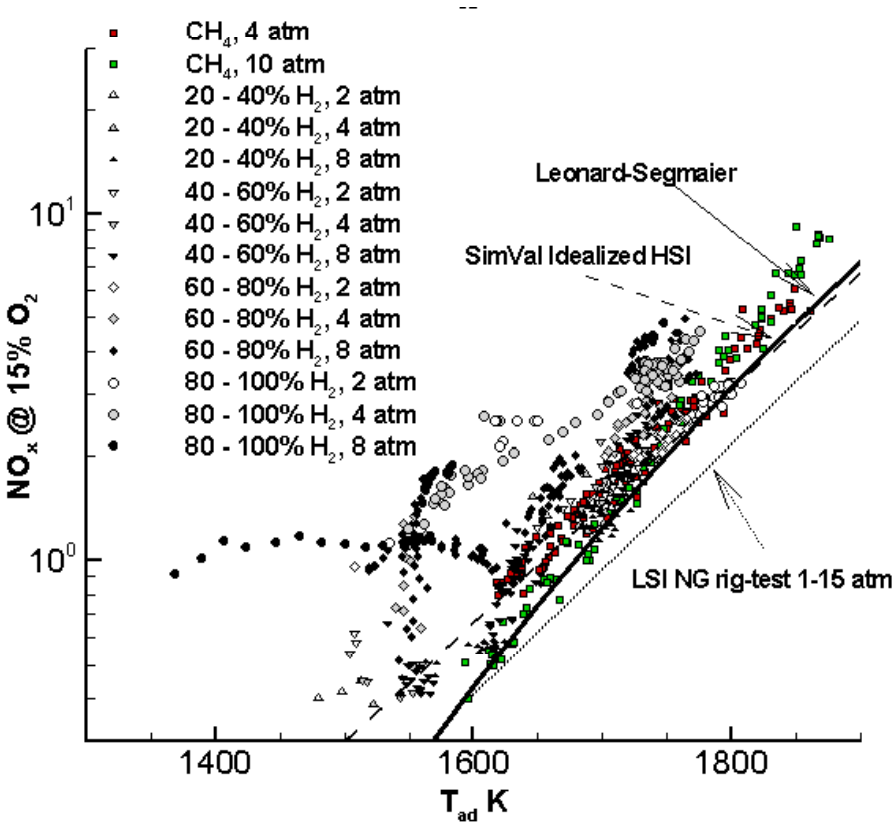
- **A typical slice of OH concentration from the simulation (left) shows indicates OH values (red) at the convex part of flame front**
- **AMR-DNS and OH-PLIF over FOV1 and FOV2 (center and right) shows that H_2 flames are "discontinuous"**
- **Discontinuity caused by H_2 depletion and not by aerodynamic strain**

Implications of OH Gaps on H_2 Turbulent Flames



- How do the H_2 flame front structures relate to the turbulent flame speed?
- Do these gaps persist at high velocities and GT conditions?
- At which H_2 % will thermal/diffusive instability affects syngas combustion?
- What type of flame models would be needed for H_2?
- What would be the appropriate analysis for H_2 flame wrinkle structures?

Can Local Hot-Spots Explains NO_x Floor Observed in SimVal?



- **Bell & collaborators included N_2 chemistry in AMR-DNS of H_2 flames**
  - **Examining local NO_x concentrations at the hot spots**
  - **Planned simulation of high-pressure flame**
- **Developing flame front analysis method for H_2 flames**
  - **Cross-correlation of local flame curvature with OH concentration from PLIF**
  - **Cross-correlation of local flame curvature, OH & NO_x concentrations, and local heat release from AMR-DNS**

Activities for FY10

- Continue the collaboration with SEI on development for F-class engines
- Develop a conceptual design for a 3-fuel LSB system and a plan for implementation and commercialization
- Characterize the effect of a divergent nozzle on H_2 operation at simulated GT conditions
- Support the development of LES for LSB
- Collaborate with NETL on SimVal high pressure studies
  - Conduct H_2 experiments at higher pressures than previous runs
  - OH-PLIF and PIV studies for selected cases
- Complete the analysis of experimental and AMR-DNS results to assess the influence of thermal/diffusive effects in CH_4/H_2 flames and the approaches to modeling the effects
- Gain preliminary insights on LSB oscillations and instability characteristics