# Low-Swirl Combustion - An Ultra-Low Emissions Technology for Industrial Heating & Gas Turbines, and Its Potential for Hydrogen Turbines

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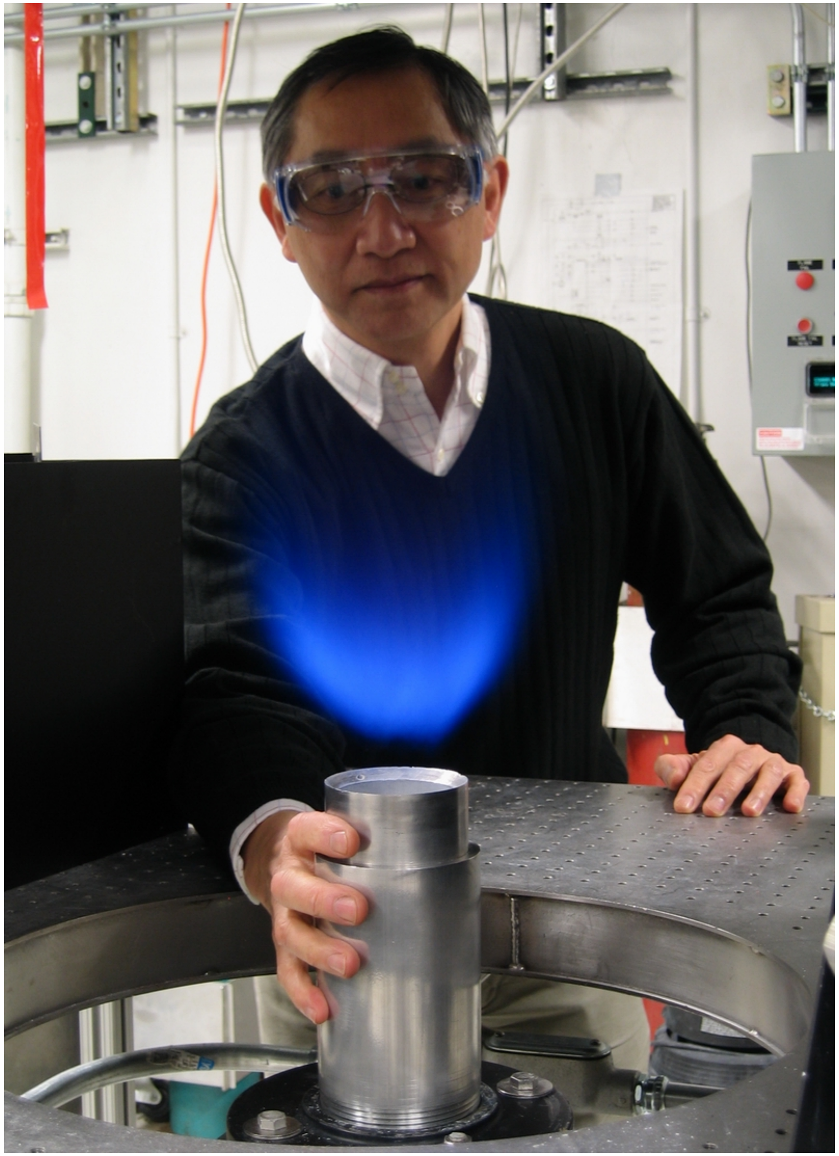
# What's Unique About Low-swirl Combustion?



- **LSC is a simple, yet sophisticated way to burn gaseous fuels (hydrocarbons & hydrogen) efficiently with very low $NO_x$ emissions by a lower cost and durable burner**

# Synopsis

- **Low-swirl combustion is a novel flame stabilization concept that is radically different than conventional approaches**
  - **Basic operating principle derived from experimental observations & analyses**
  - **Active research topic not covered by combustion text books**
- **LSC is an ultra-low emissions enabling technology for heating and power systems**
  - **Great attributes:**
    - **Scalable - 7 kW (1") to 14 MW (16") burners due to linear characteristics**
    - **Robust - < 2 ppm $NO_x$ (@15%$O_2$) without exhaust gas clean-up or tight controls, high turndown (30:1), fuel flexible, and reliable**
    - **Low-cost - simple design made of conventional materials, size & form compatible with current designs, and adaptable without re-configuration**
- **Analytical tools available to guide future developments**
  - **Less uncertainties & more predictabilities to**
    - **scale to the capacity and high T, P conditions of large utility turbines**
    - **develop fuel-flexible low-swirl combustors for gaseous hydrocarbons, landfill gases, biomass gases, refinery gases, syngases and hydrogen**

# Agenda

| Time | Topic |
|---|---|
| **10:05 AM** | **Introduction to Low-swirl Combustion<br>Theoretical background, review of LSC operating principle, development history, and overview of recent accomplishments.** |
| **10:30 AM** | **Q&A on LSC Technology.** |
| **10:35 AM** | **Technology Transfer Experiences<br>Adaptation and scale-up for Maxon industrial burners<br>Development for Solar Turbine 7 MW Taurus engine** |
| **10:55 AM** | **Q&A on Data from applications** |
| **11:00 AM** | **Empirical model for LSC adaptation to large scale turbines for natural gas, syngas, and hydrogen fuels.** |
| **11:15 AM** | **Q&A on Potential Applications** |
| **11:20 AM** | **Scale-up issues and challenges for IGCC** |
| **11:30 AM** | **Q&A on Scale-up Issues and Challenges** |
| **11:35 AM** | **Needed R&D to address potential Issues and challenges** |
| **11:50 AM** | **Q&A on Needed R&D** |
| **11:55 AM** | **Wrap-up** |
| **Noon** | **Adjourn** |

# Part 1:

# Introduction to Low-swirl Combustion

## Theoretical Background,

## Review of LSC Principle

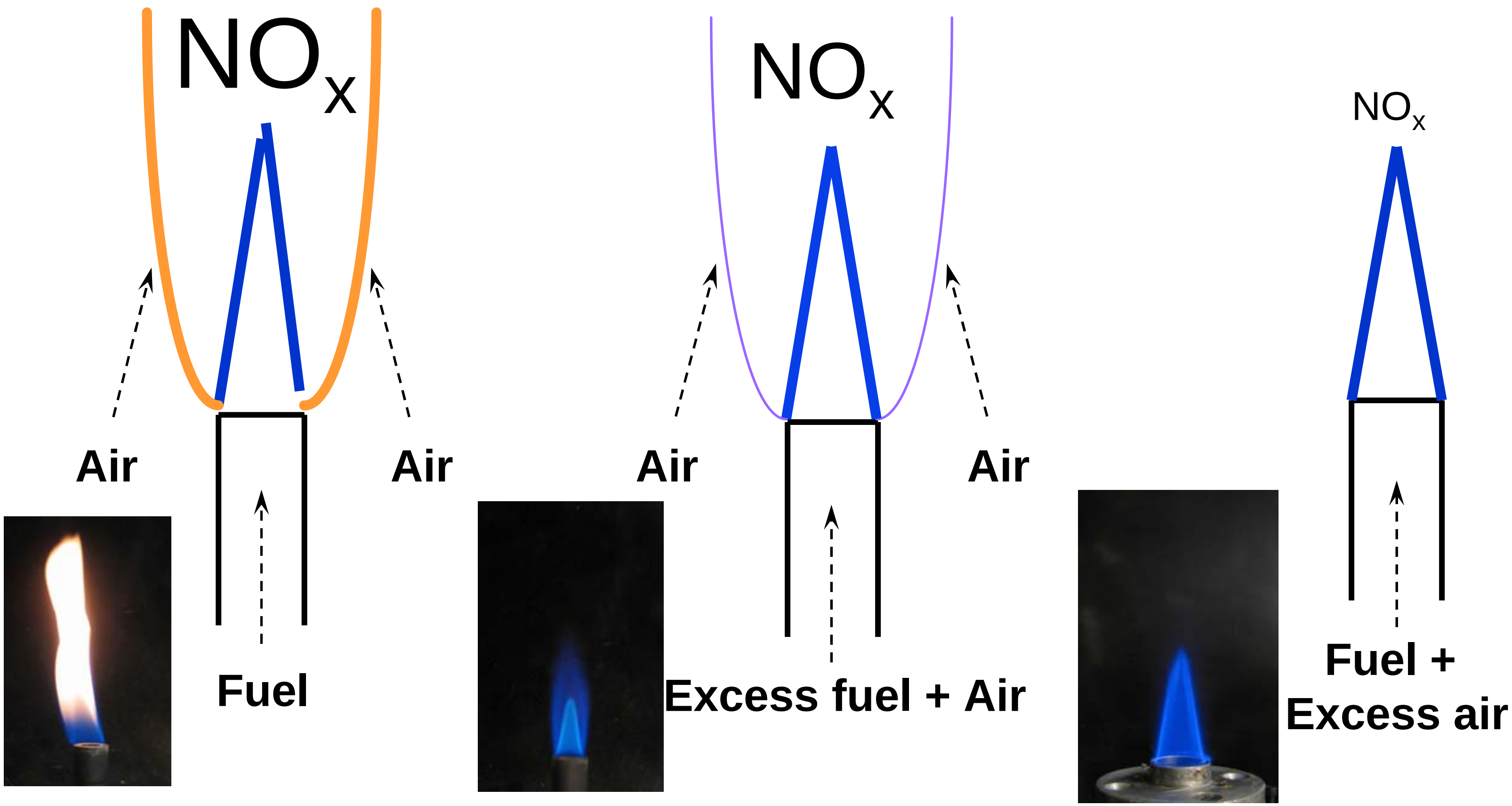
## Development History

## Overview of Recent Accomplishments

# Combustion Science and Technology

- **One of the oldest technologies of mankind**
  - **Created and destroyed civilizations**
  - **Combustion provides 83% of US energy**
- **Highly refined art of combustion engineering**
  - **Contemporary systems with high efficiency and reliability**
  - **Development and testing cycle absorbed much resources**
- **Relatively new scientific discipline**
  - **Sophisticated research tools – advent of lasers and computers in the 1970s**
  - **Diverse topics and scope - rocket engines, aircraft engines, gas turbines, burners, boilers, incinerators, fires and smoldering combustion**
  - **Multi-disciplinary - chemistry, physics, mechanical engineering, chemical engineering, civil engineering, and computational science**
  - **Highly specialized practitioners – expertise for each specific combustion system (transportation, power, manufacturing, aerospace, military, fire safety etc.)**

# Modes of Gaseous Combustion



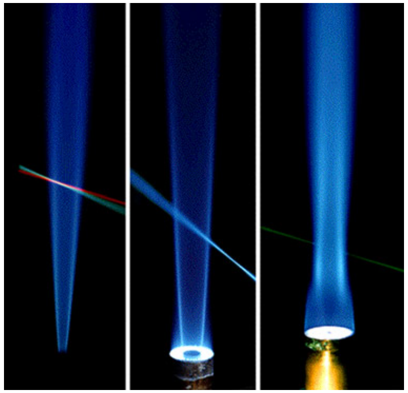

**Diffusion Flame**
**controlled by mixing**

**Partially Premixed Flame**
**two reaction zones**

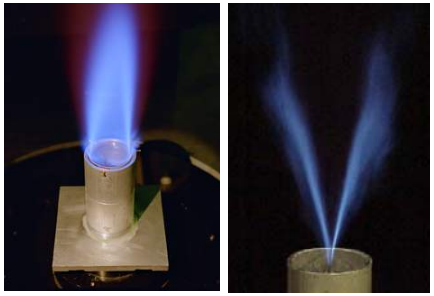
**Lean Premixed Flame**
**wave-like flame front**

# Turbulent Combustion Occurs Naturally in All Practical Systems

- Important research topic of physical sciences
- No unified theory due to differences in combustion modes

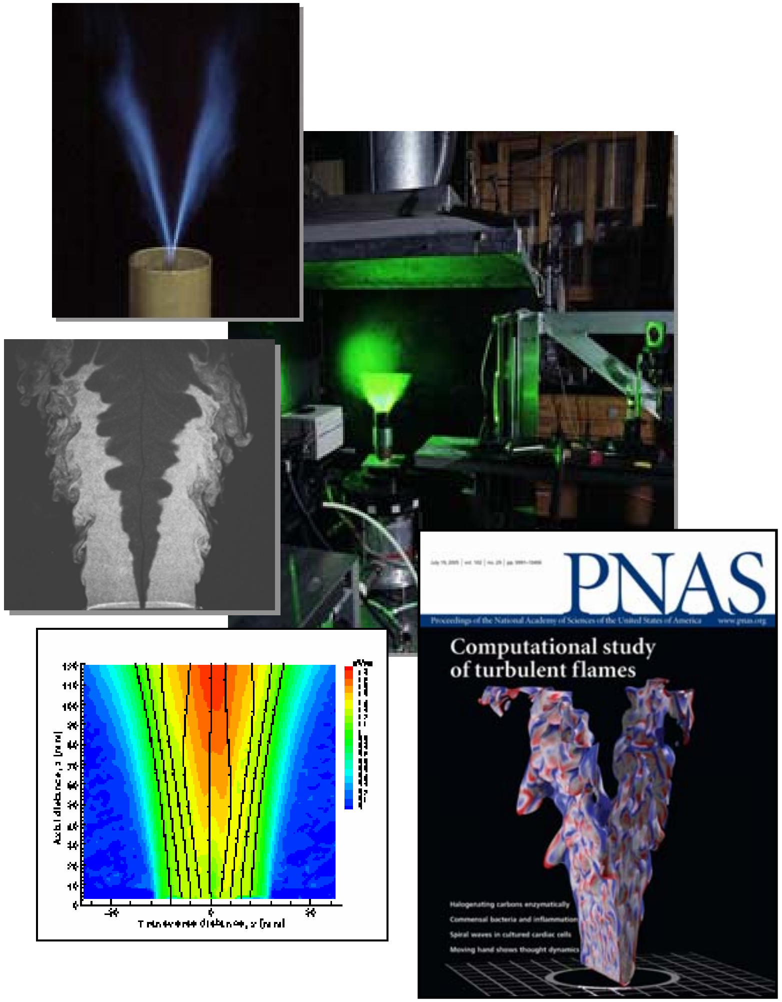


- **Non-premixed (diffusion) flames**
  - Turbulent and molecular mixing control combustion rates, efficiency and pollutant formation
    - Reactions occur at stoichiometric contours passive to turbulence
  - Reaction rate models expressed in terms of species concentrations



- **Premixed flames**
  - Self propagating flame front separates reactants from products
  - Flame front exhibits wave behavior and generates significant feedback to turbulent field through the pressure field
  - Reaction rate models expressed in terms of flame speed

# LBNL Combustion Research Focuses on Premixed Turbulent Flames




Numerical simulation of a rod-stabilized v-flame validated by detailed velocity and scalar data

- **Motivation:** Turbulence and fluid mechanics dominate flame processes
  - Chaotic and random fluid motions controlling heat release, emissions, & explosion limits
- **Scientific Needs:** Fundamental understanding of flame/turbulence interactions
  - Laboratory burners with well characterized turbulence fields that offer broad range of operating conditions are critical tools
  - Statistical data analysis methods to validate theories and simulations

# Turbulent Combustion as an Applied Research Problem

- **Flames burning in complex turbulent flowfields**
  - **Flame behavior not always predictable**
- **Need scientific foundation to reduce R&D cost**
  - **Moving away from handbooks to computational design tools for advanced combustor designs**
  - **Improve performance – turndown, emissions, reliability and durability**
  - **Reduce production and maintenance costs - avoid costly materials and catalysts for exhaust gas cleanup**
  - **Intelligent deployment of sensors for control**
    - **Characterize flame behavior during power turndown**
    - **Understand precursors to instability, flashback and blowoff**

# Flames in Large Industrial Applications and Power Generation Systems

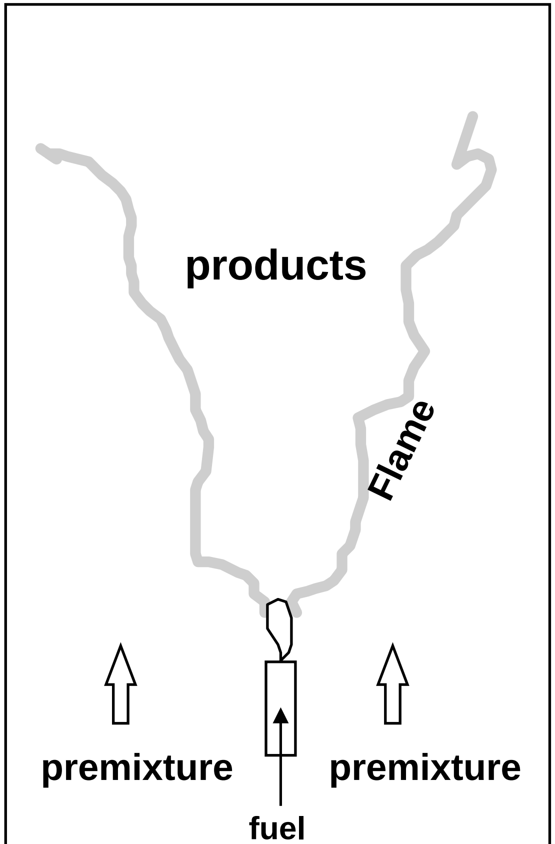
- **Most burners and combustors exceed 99% efficiency**
  - **Design challenges concerned with optimizing efficiency & emissions**
- **Non-premixed or partially premixed flames cannot meet stringent emissions rules without costly exhaust gas cleanup**
- **Lean premixed combustion or multi-staged combustion concepts do not require exhaust gas cleanup to meet emissions targets**
- **Tight control and monitoring deemed essential for ultra-low emission**
  - **Navigating startup, load change, and off-normal situations**
- **“Stationary sources” subjected to most stringent emission regulations**
  - **Operate continuously with few interruptions ( > 20000 hr. non-stop)**
  - **Low “Single digit $NO_x$” requirement planned for most of CA and regions in TX, LA, and Northeastern States**
  - **Near-zero emissions target for DOE-Clear Power Systems**

# Issues of Lean Premixed Combustion for Heating and Power

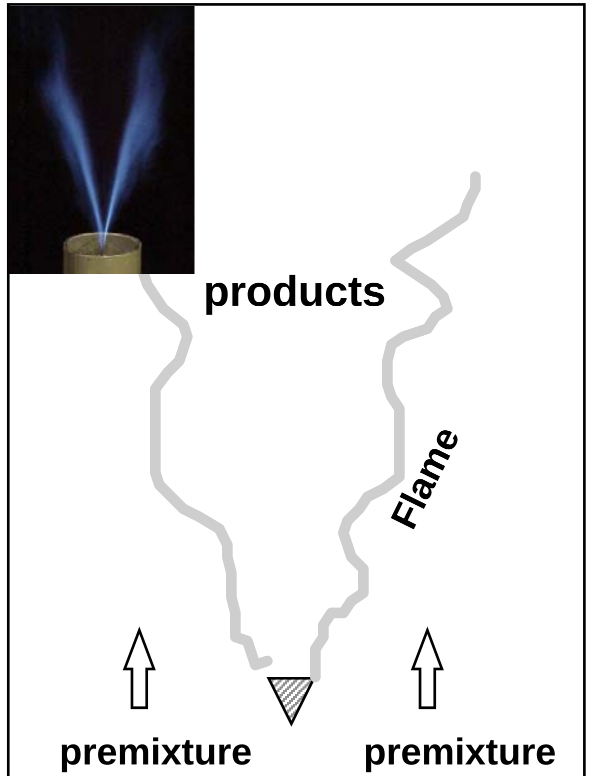
- **Limited knowledge on turbulent flame behavior**
  - **Turbulence, fuel type, operating conditions affect flame speed, burning rates, flame size & emissions**
- **Flame holders dictate flame shapes and behaviors**
  - **Restriction on operating range ( typically 5:1 turn-down vs. 10:1 for non-premixed systems)**
  - **Limited fuel flexibility**
- **Flame generated flow dynamics**
  - **Strong flame/chamber coupling**
  - **Weaker lean flames generates noise and vibrations**
  - **flash-back and blow-out hazards**

# Conventional Premixed Flame Holders

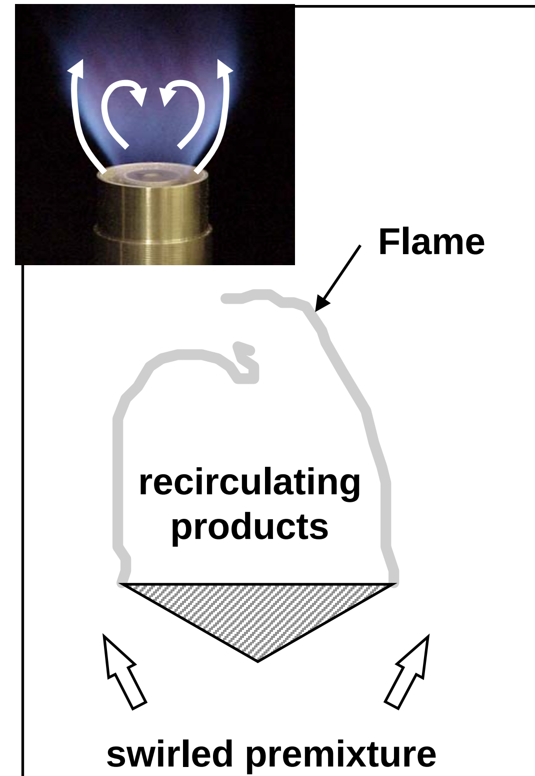
- **Theoretical explanation based on continuous ignition provided by pilot flame or in the hot recirculation zone in the wake of the stabilizer**
- **"Back flow" within the recirculation zone is considered essential**




**Pilot Flame**

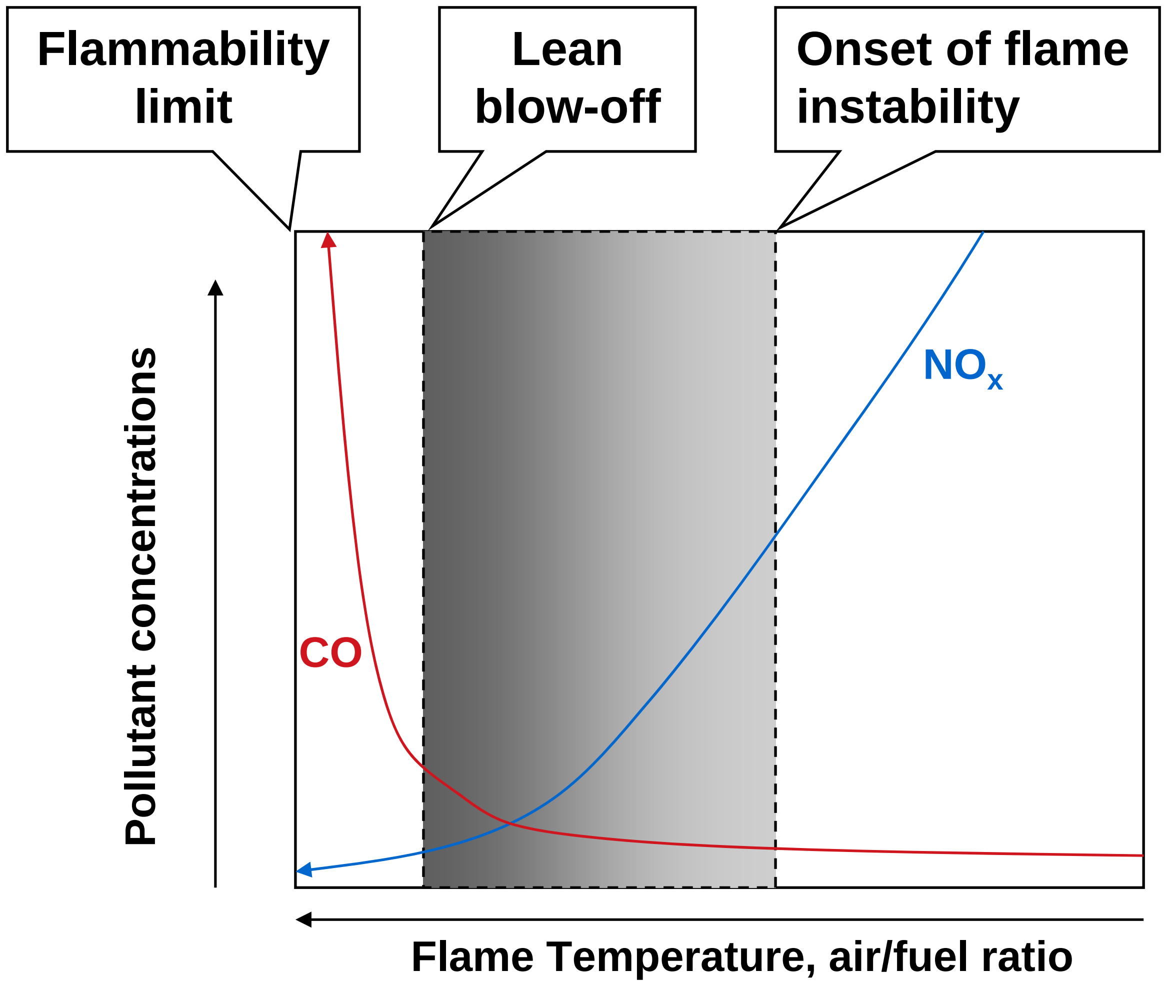



**V-gutter**

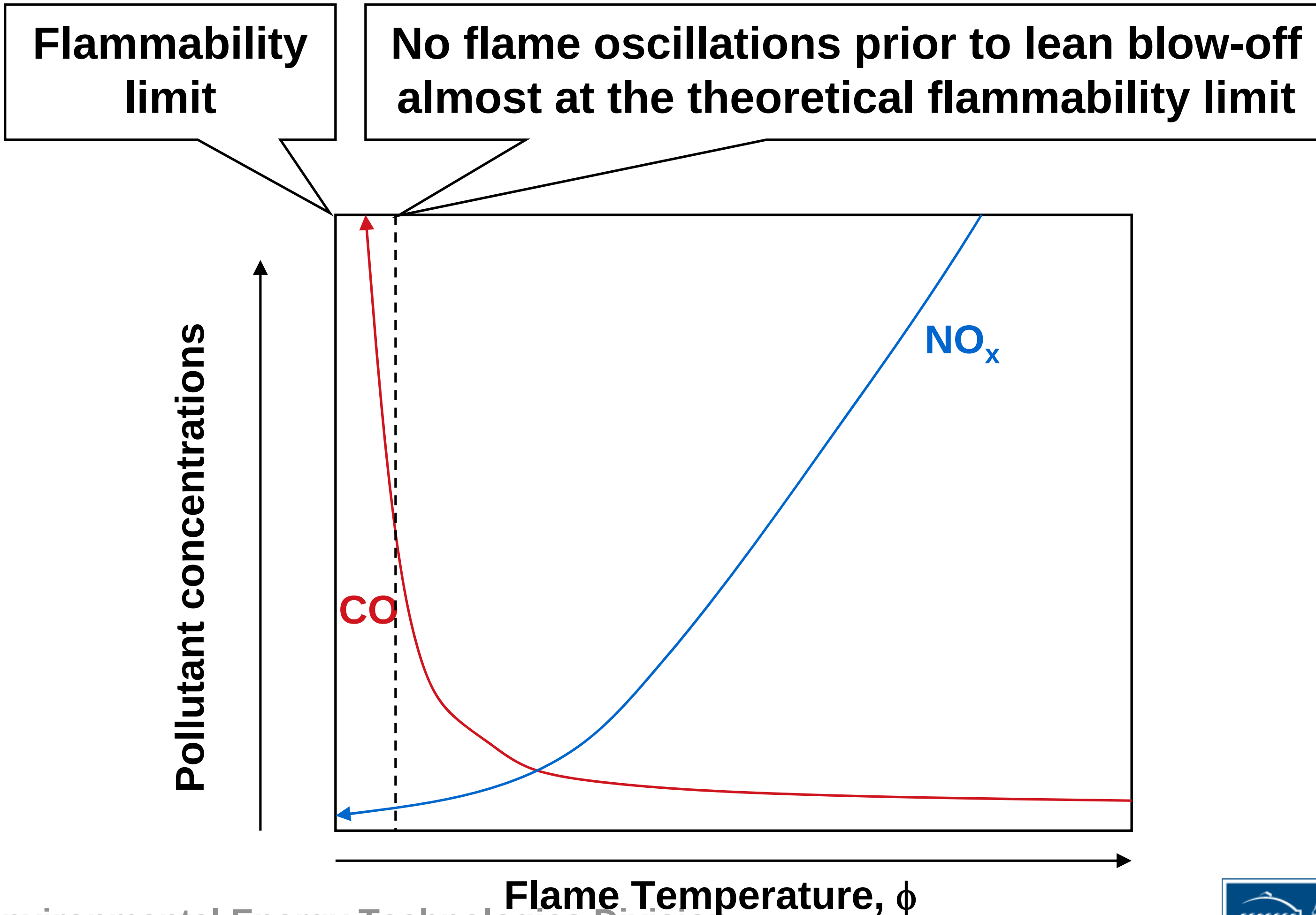



**Bluff Body + High Swirl**

# Lean Blow-off and Flame Instability Limits of Flame Holders Are Barriers to Reaching Ultra-Low Emissions



# Low-swirl Combustion Exploits Aerodynamics to Overcome the Ultra-Low Emissions Barriers



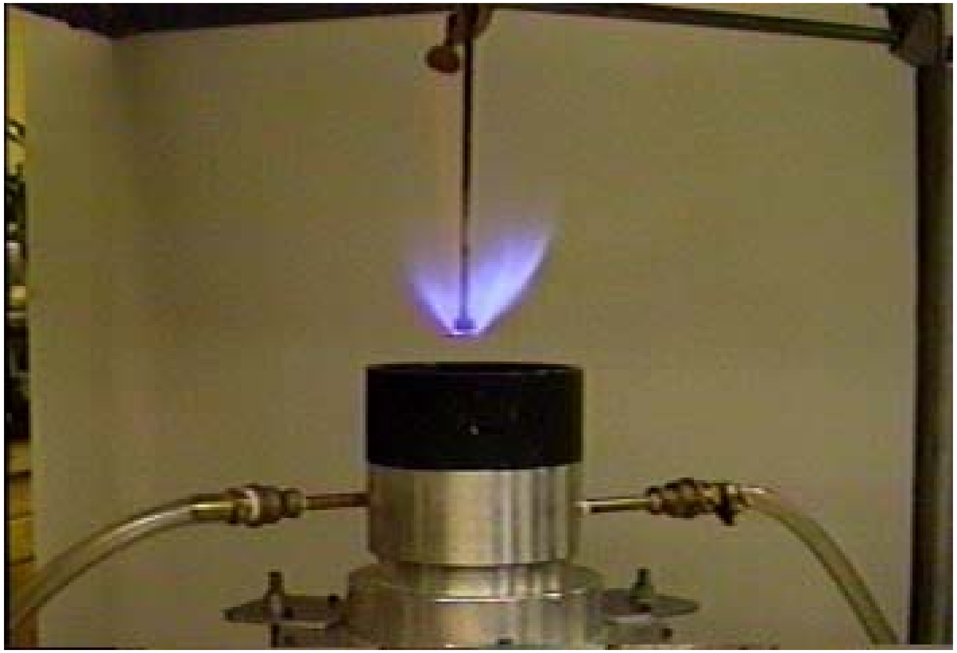
# Low-Swirl Combustion (LSC)

- LSC is a flame stabilization mechanism conceived at LBNL for DOE supported basic research
  - Excellent experimental configuration
    - Supports stable premixed flames in intense isotropic turbulence and at conditions from near flame-out to high stoichiometries
    - Operating principle derived from experiments and analyses
      - Exploits turbulent flame speed, $S_T$ - the most fundamental property of the premixed flames
      - Not applicable to non-premixed combustion
    - Adopted by researchers world-wide
  - Technology transfer
    - LSC supports robust lean flames with ultra-low emissions
    - 2 US patents
      - Flame stabilization principle
      - Vane-swirler design
    - Basic knowledge facilitates development of scaling and engineering rules and practical implementation

# Video Demonstration of How Low-Swirl Combustion Eliminates the Flame Holder

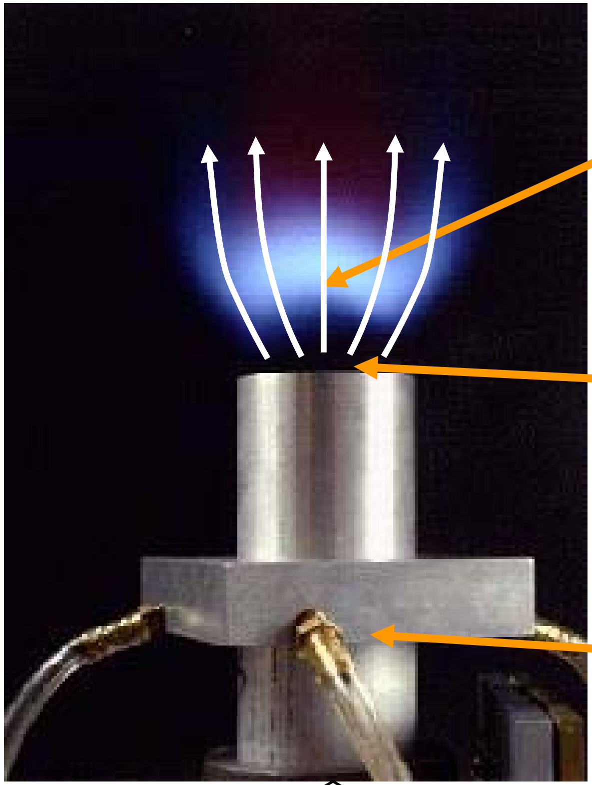
- **The first generation low-swirl burners utilize air-jet to generate swirling motion**
- **The still image below shows the flame anchored to the central stabilizer when the two jets are off**

**Turning on and gradually increasing the air-jets show transition from anchored to lifted flame**



**http://eetd.lbl.gov/aet/combustion/LSC-Info/LSB%20Initiation.mpg**

# Low-Swirl Flame Stabilization Exploits Propagating Nature of Premixed Flames



Propagating against the divergent flow, the flame settles where the local velocity equals the flame speed

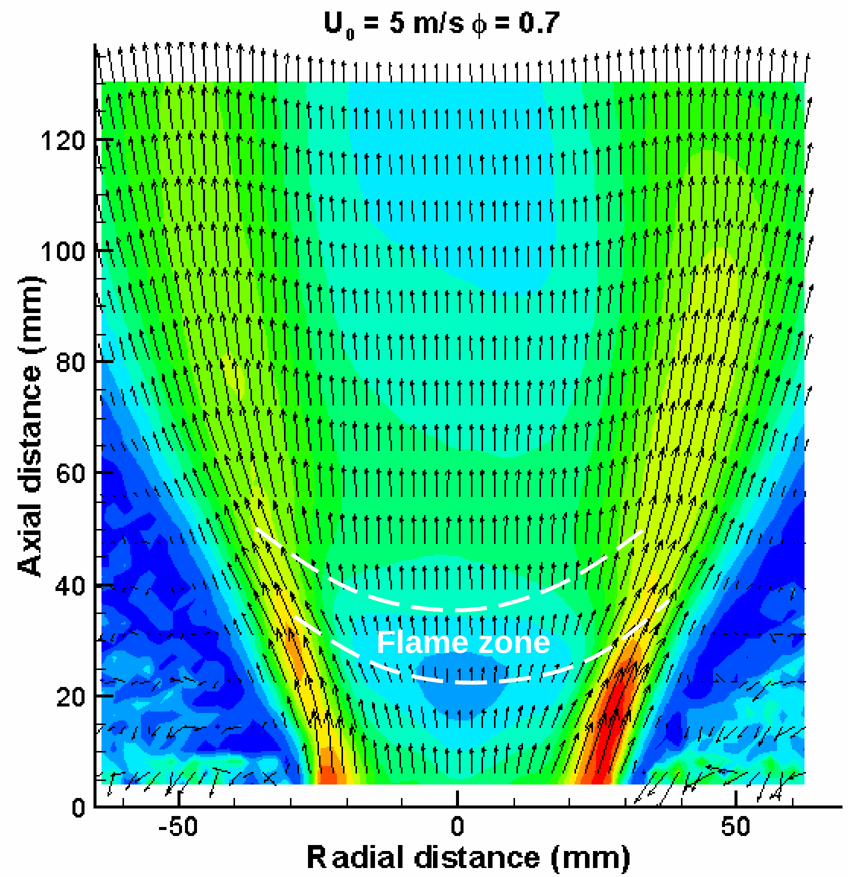
Flow divergence within the **non-swirling** central region is the key element for flame stabilization

Small air jets swirl the perimeter of the fuel/air mixture but leave the center core flow undisturbed

Fuel/Air mixture

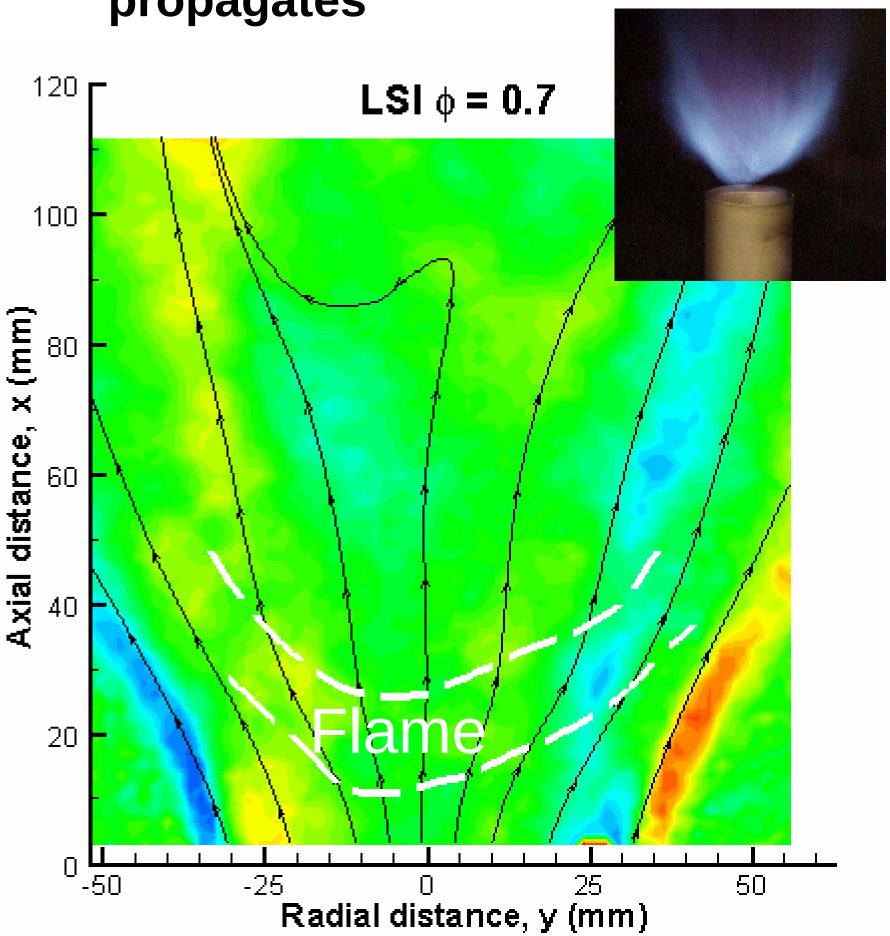
# Flame Stabilization Mechanism Characterized by Laser Diagnostics

- LSC does not requires "back flow" to stabilize turbulent premixed flames
- Flow divergence rate controlled by swirl rate
- Turbulence intensity provides the feedback to increase flame speed as flow velocity increases
- Flame position invariant through wide range of inflow velocities and fuel/air ratios due to flowfield similarity
- Flame flow coupling described by top level model to guide engineering design

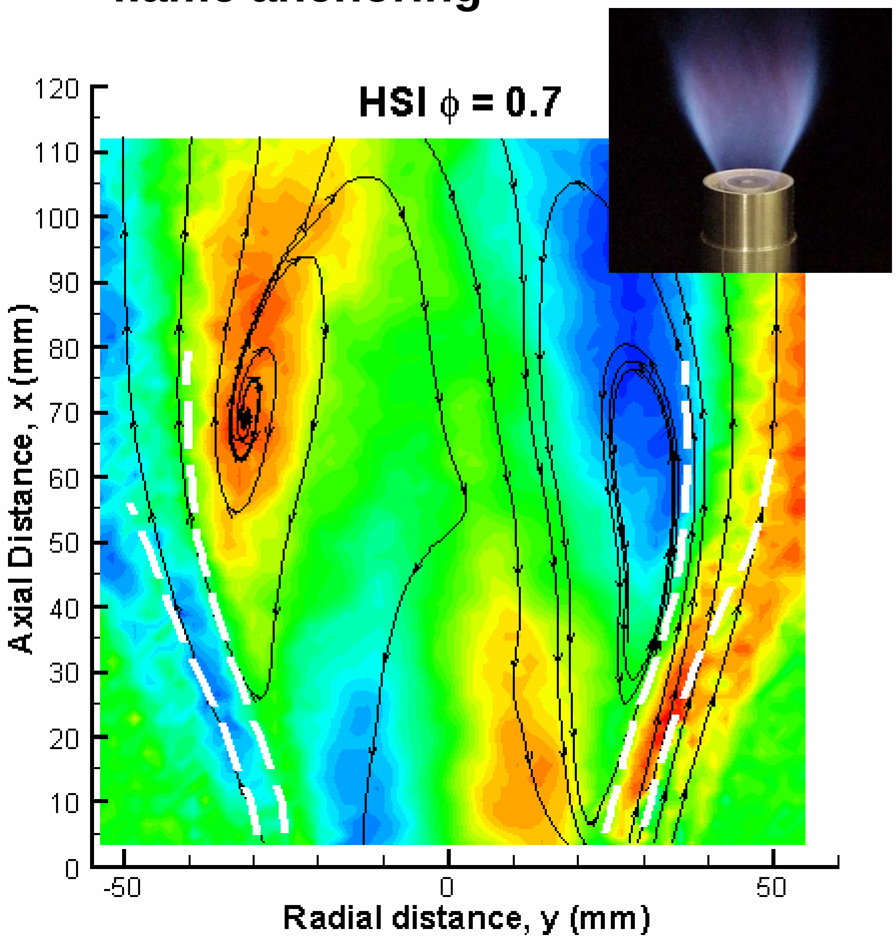


# Comparing Flowfields of Low-swirl and High-swirl

- **Low-swirl injector generates flow divergence where the flame freely propagates**




- **Conventional high-swirl injector generates recirculation flow for flame anchoring**



# LSC is Fundamentally Different than High-Swirl Flame Stabilization

- High-swirl combustion processes dictated by fully developed large recirculation zone
  - hot combustion products trapped in the vortex continuously igniting the surrounding swirling reactants
  - nonlinear flame flow coupling involving vortex breakdown and precessing vortex core
  - Lower level models required for engineering design using computational fluid dynamics
- Onset of intermittent flame detachments from centerbody are precursors to blowout
- Need to mitigate instabilities & oscillations at ultra-lean conditions
  - Staged “rich-quench-lean” method
  - Active feedback control
  - Catalytic pilot or combustor

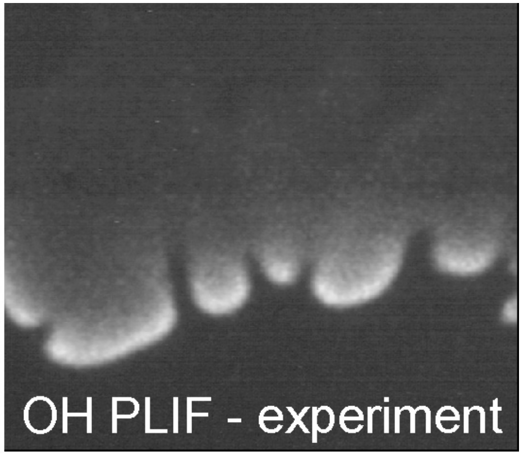
# Low Swirl vs. High Swirl for Flame Stabilization

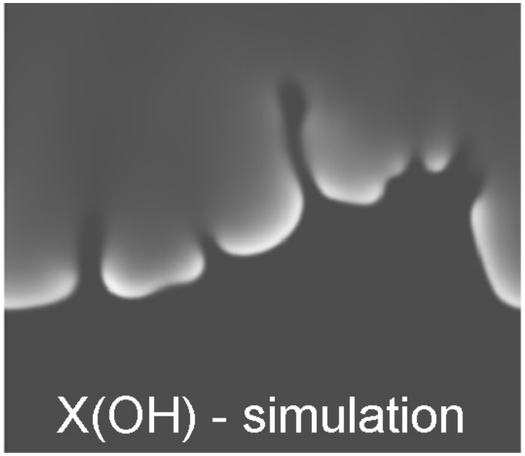
| | Low Swirl | High Swirl |
|---|---|---|
| Principle | Flame propagates freely at its turbulent flame speed | Vortex traps hot products for continuous ignition of fresh mixtures |
| Approach | Generation of divergent flow with no recirculation | Generation of tight recirculation zone |
| Flame/ turbulence interaction | Flame developing in isotropic turbulence with low shear stresses is less prone to fragmentation | Flame developing in high shear region leads to flame fragmentation and occasional detachment |
| Instability | No distinct characteristic frequency due to absence of recirculation | Characteristic frequencies associated with recirculating vortex |

# LSC as a Research Tool

- LSC produces a lifted premixed turbulent flames giving free access to laser diagnostics
- Near planar flame brush locally normal to the approach flow gives a close approximation of a slightly stretched 1D premixed turbulent flames for comparison with models
- Developed a benchmark low-swirl burner with Swedish and German scientists for validation of models and simulations

- Turbulent $H_2$/air Flames Studied in a Low-swirl Burner



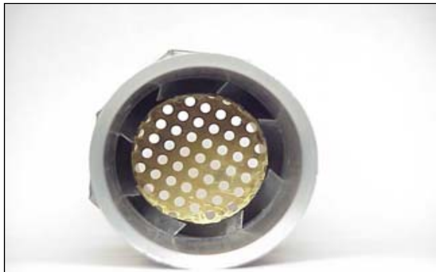




- LBNL computational researcher developing 3D direct numerical simulations of turbulent flames using detailed chemical kinetics
- Measurements and simulation show $H_2$/air flames are locally quenched and calls question to the validity of conventional flame models for $H_2$/air flames (31st Sym. Paper)

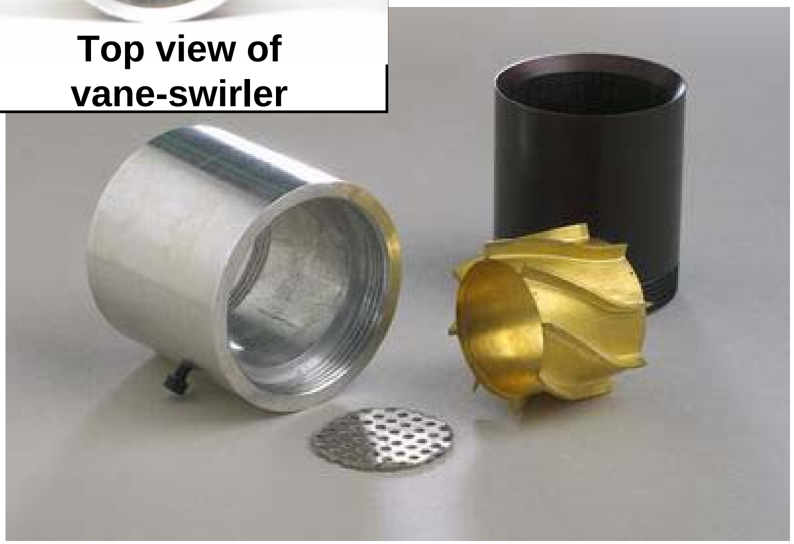
# First Technology Transfer Project Supported by DOE-LTR (1994-1997)

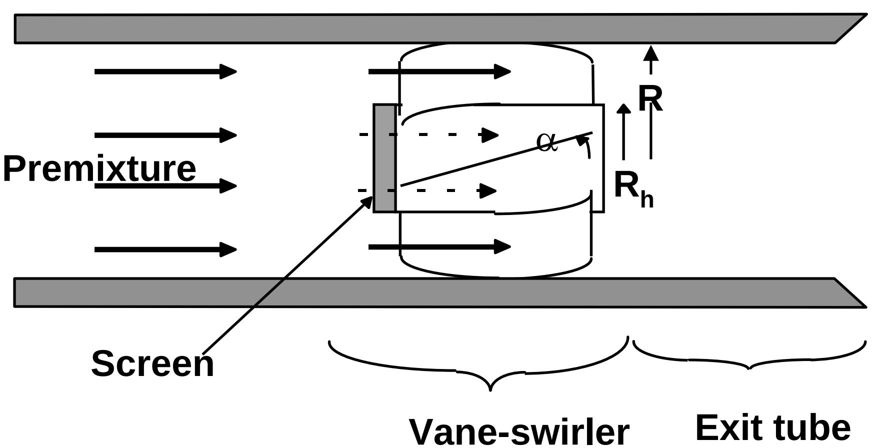

- Adaptation to pool heaters
  - Design and test LSBs that meets the operational requirements of 15 KW to 100 KW units
  - Sizes similar to laboratory LSBs
  - Non-modulated systems, no turndown requirement
- Issues
  - need simpler design requiring only one flow supply (NO JETS)
  - firing sideways or downwards to attain > 85% efficiency
  - stable inside chamber
  - cannot compromise on energy efficiency
  - cost must be lower than metal fiber burner ( < $100/per unit)

# Vane Swirler for LSC



Top view of vane-swirler






- **Reactants pass through two passages – swirled and unswirled**
- **Non-swirling core inhibit flow recirculation**
- **Perforated screen covering center channel balances the ratio between swirling and non-swirling portions**
- **Modified definition of swirl number, S**

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

- Center channel to injector radii ratio , $R = R_c/R_b$
- Vane angle, $\alpha$
- Flow split between center channel and swirl annulus, $m$

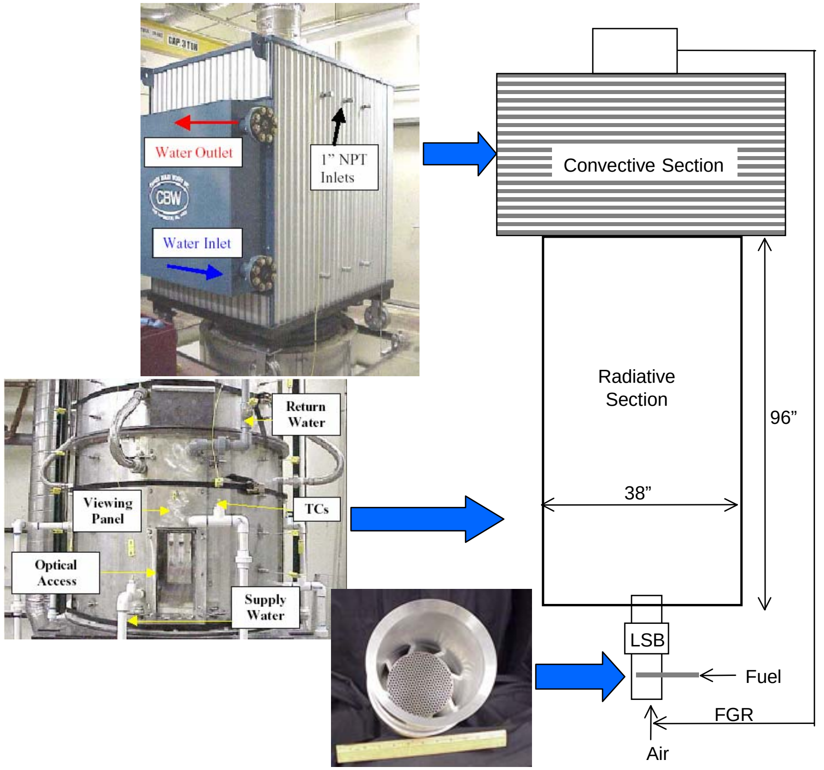
# Vane-Swirler for LSB Can Be Made From Simple and Low-Cost Materials

This burner is made of PVC and plastic to showcase the uniqueness of LSB

- **Vane-LSB produces the same flame shape as Jet-LSB**
- **Lifted flame does not transfer significant heat to burner**
- **Estimated fabrication cost for pool heaters < $10/unit**

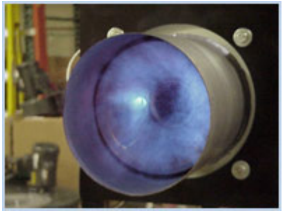
# LSC for Industrial Heating

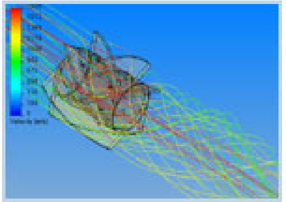
- **Scaled to larger capacities**
  - **Laboratory studies to determine scaling approach and establish scaling rules**
  - **Developed and tested prototypes for large boilers with or without flue gas recirculation**
  - **Further development for direct heat applications**
- **Maxon Corp. licensed LSC in 2002 for ultra-low $NO_x$ burners for industrial heating, baking and drying**
  - **< 9 ppm $NO_x$ (@ 3% $O_2$) guaranteed**
  - **"Achieved industry best emissions without sacrificing cost or performance"**

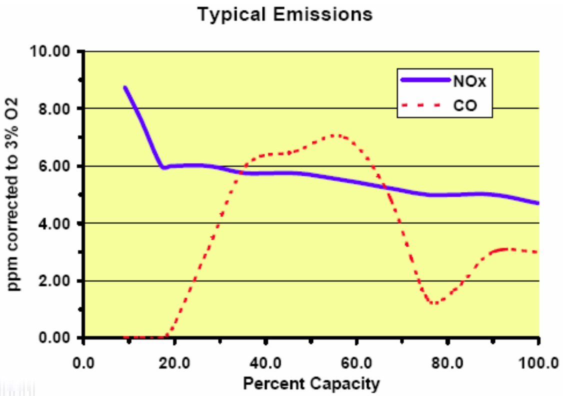


# Maxon Has Two LSB Product Lines

- **4-7 ppm $NO_x$ (@3%$O_2$) = 1.5-2.5 ppm $NO_x$ (@15%$O_2$)**
- **M-PAKT burners (0.5 – 3.5 MMBtu/hr) available since 9/03**
  - **2”, 4” and 6” burner diameter**
  - **Fuel flexible with natural gas, propane and butane**
  - **10:1 turndown without pilot assistance**
  - **Hundred of units installed**
  - **Improve product quality (paint curing & food processing)**
  - **1st unit operating continuously since 2/02**
- **OPTIMA SLS gas/liquid dual-fuel burners (12 - 50 MMBtu/hr) introduced in 2006**
  - **8”, 10, 12” and 16” burner diameters**
  - **enhanced 13:1 turndown**
  - **backup liquid fuel firing**
  - **Two prototypes installed & several units in production**






SLS™
shear layer stabilization

# Development for Gas Turbines

- **DOE Office of Electricity - adaptation of LSC to Solar Turbines' Taurus 70 engine that utilize natural gas, renewable fuels and on-site generation fuels**
  - **Proved LSC concept for gas turbines**
- **California Energy Commission - development of a packaged combined heat and power system consisting of a boiler with a Coen Micro-$NO_x$ burner and a Elliott microturbine with a LSC combustor**
- **DOE Fossil Energy - new project to develop low-swirl combustion as an enabling technology for advanced turbines in IGCC power plants utilizing high $H_2$ fuels**

# Part 2

# Technology Transfer Experiences

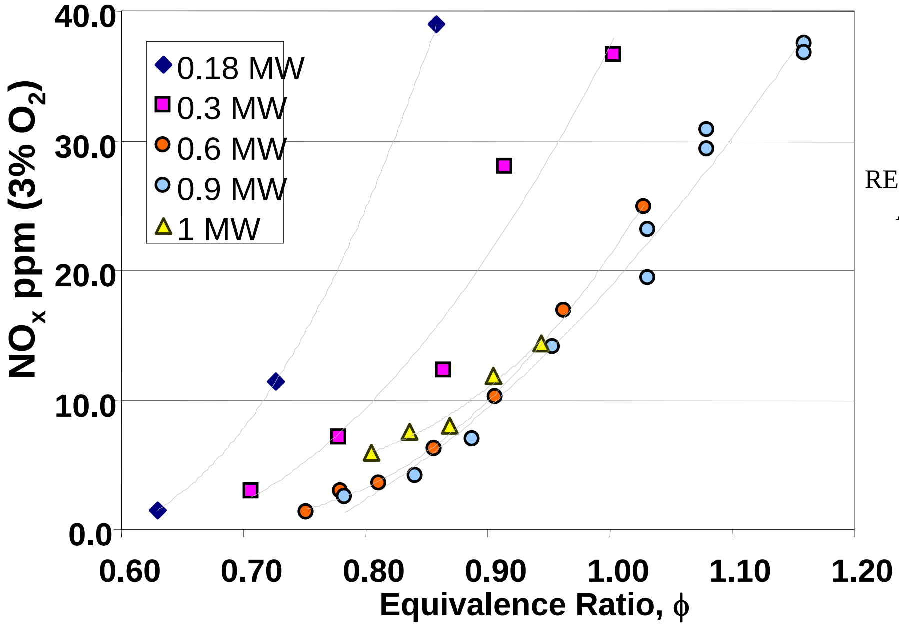
## Adaptation and scale-up for Maxon industrial burners

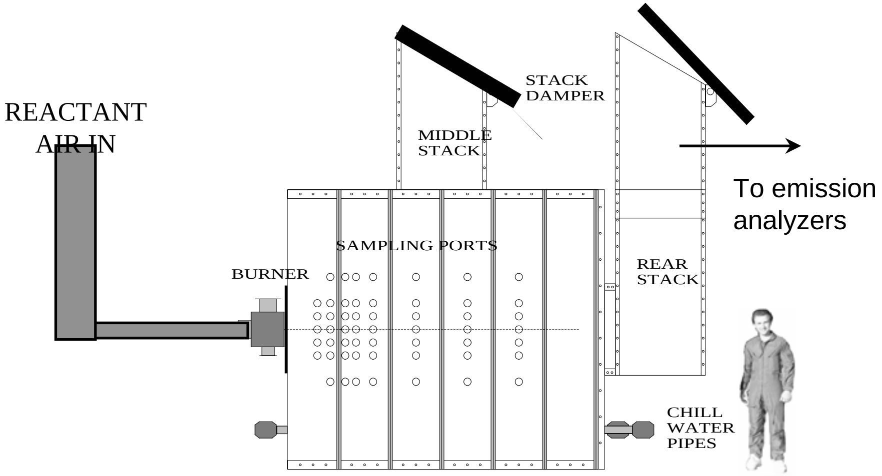
## Development of low-swirl injectors for Solar Turbine Taurus 70 engine

# Adaptation of LSC to Industrial Burners

- DOE-EERE Industrial Technologies Program fostering "*Scientific approach for 'smart' adaptation to a broad range of process heat and boiler applications*"
  - Targeted 300 KBtu/hr to 50 MMBtu/hr burners
- *Established scaling rules*
  - Grounded on low-swirl combustion principle
  - Considered blowout and flashback characteristics
  - Evaluated trade-off/benefit between two scaling approaches
    - Higher flow velocity vs larger burner diameter
  - Optimized burner to combustion chamber size and geometry

# Laboratory Experiments to Gain Scaling Information



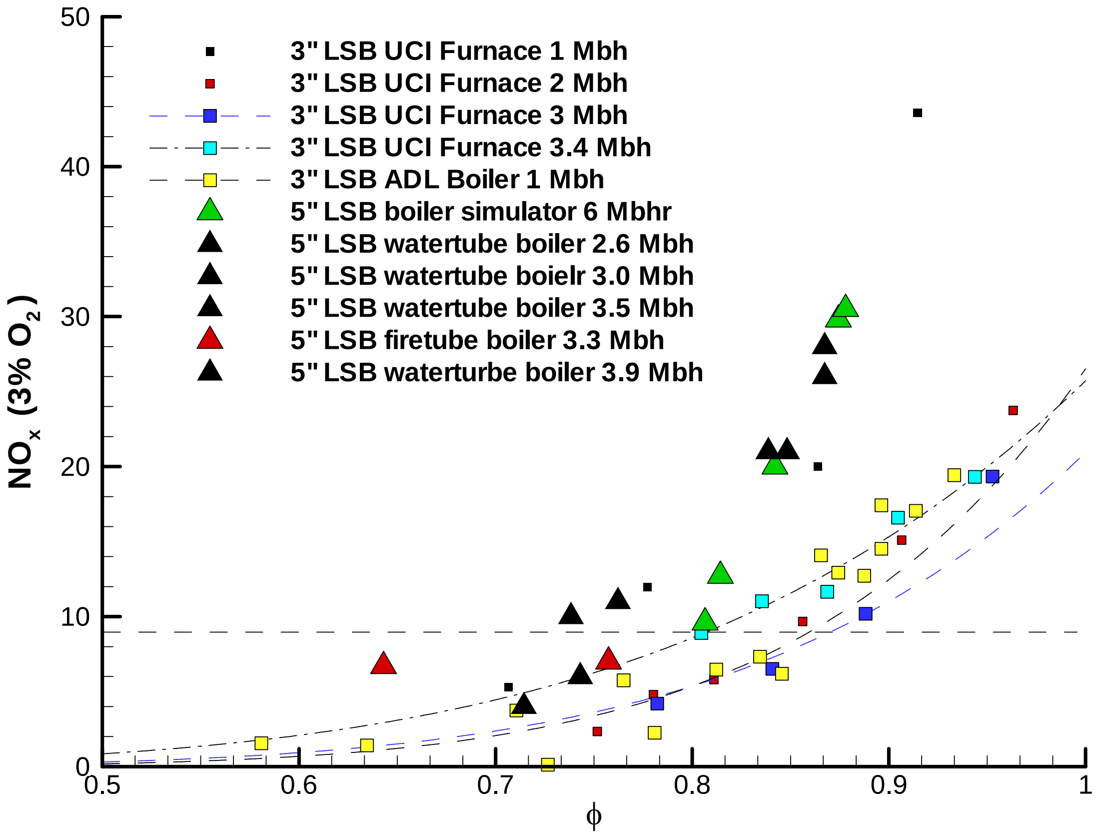




- **Comparing LSBs of different sizes (2 – 5") in furnace and boiler simulators with and without FGR**
  - **Vane shape, screen placement and small changes in swirl number have little effect on flame noise, flame stability, & lean blow off**
  - **$NO_x$ emissions depend primarily on air/fuel ratio (i.e. flame temp.)**
  - **Observed 30:1 turndown**

# LSB Scaling Rules

- Keep swirl recess at 1 to 1.5 diameter
- Apply 0.4 < S < 0.55 criterion
  - **Center-channel/burner ratio 0.5 < R < 0.6**
    - **Larger R increases drag thus blower power**
  - **Vane angle between $37^0$ to $45^0$**
    - **Vane can be curved or straight, overlapping vanes increase turndown**
  - **Use different screens to change S**
    - **Screen geometry is not critical, other options available to change *m***
- Constant velocity scaling for power output
  - **Output power scaled by the square of the burner diameter**
- Optimum flame closure at 3 to 4 $R_b$

# Applied 0.4 < S < 0.55 Criterion to Scale LSB up to 16" and 50 MMBtu/hr




- $NO_x$ correlates primarily with air/fuel ratio
  - Chamber geometry has some effect due to internal flow pattern and residence time
  - Cross < 9 ppm (3% $O_2$) threshold at 3% to 5.5% $O_2$
- LSB flame is quiet and remains stable even at high excess air and FGR

# Basic Understanding Helped Practical Implementation

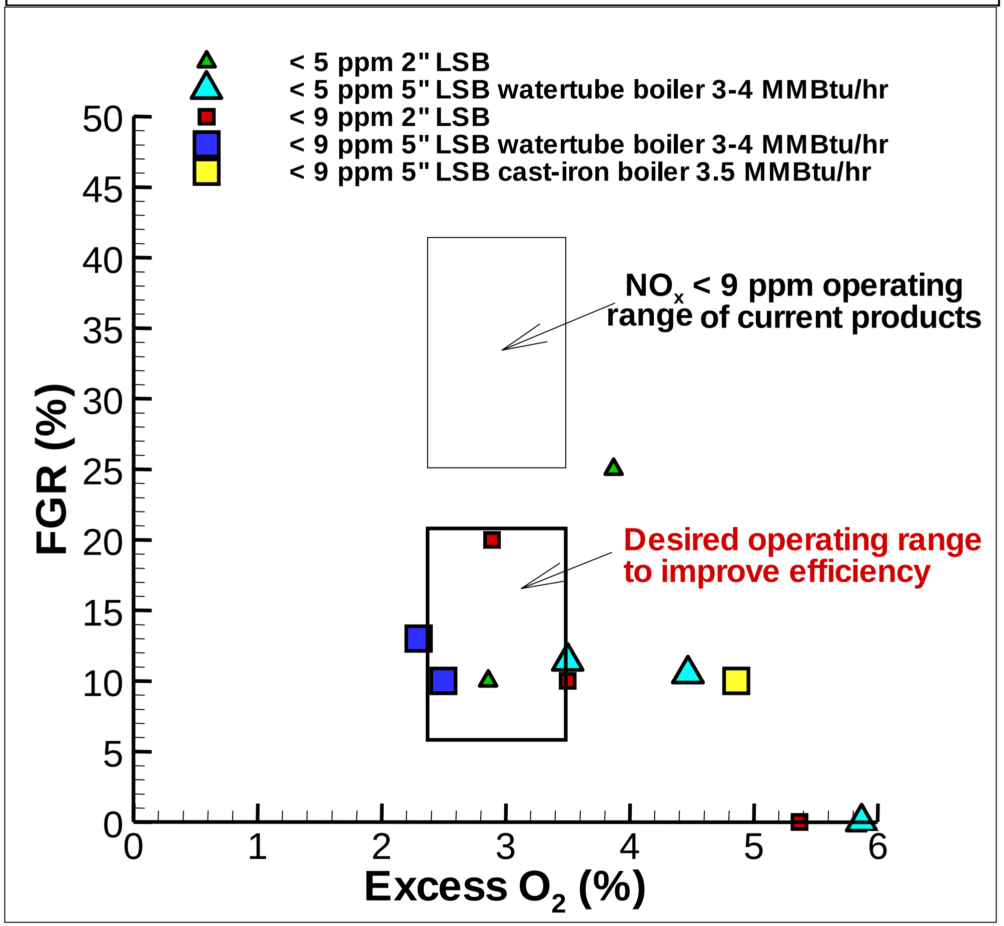
- Applied theoretical knowledge on
  - **Turbulence scaling, production, and dissipation**
  - **Flame temperature, flame speed and reaction chemistry**
  - **Combustion aerodynamics**
- Identified, prioritized and resolved operational issues on
  - **Placement of flame ignitor**
  - **Protocol to maintain flame stability during load change**
  - **Premixing requirement**
  - **Conditioning of flow supplied to the burner**

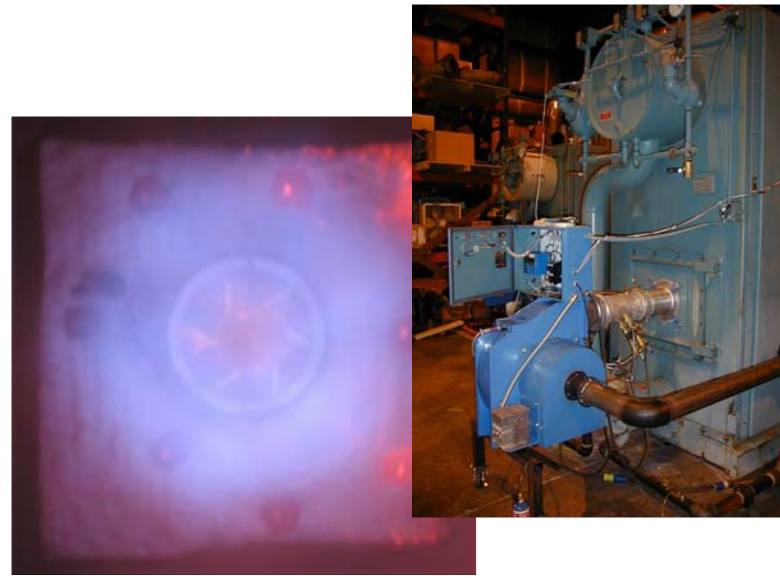
# Maxon Identified Significant Economic and Technical Advantages of LSB

- **Design scales by governing equations**
  - **A radical departure from experimentation approach**
- **Size compatible to existing equipment**
- **Can be fabricated with no initial re-tooling or new patterns required - fewer parts from common materials**
- **Operates on conventional fuels (e.g. natural gas & propane) and uses flow controls designed for high $NO_x$ burners**
- **Flame is not in contact with burner tip**
  - **No thermal stresses to cause metal fatigue**
- **Lower operational cost, and greater ease of operation, owing to a simple combustion process**

# LSB Tested in Commercial Watertube & Firetube Boilers with External FGR

LSB points for < 9 & < 5 ppm $NO_x$ (@3% $O_2$)

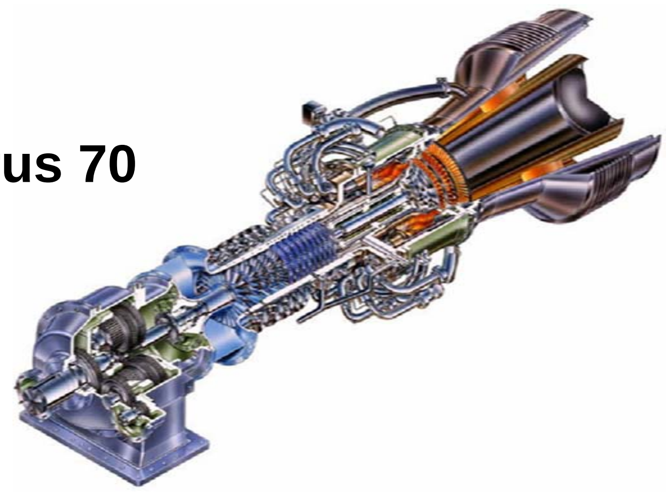


- **Use blower and controls for the commercial boiler**
- **Demonstrated low $NO_x$ at partial load**
- **In-chamber flow pattern alters $NO_x$ formation**
- **LSB shows good promise for improving system efficiency**

# DOE-DER Low-emission Turbine Project with Solar Turbines

- LSC to meet metrics for DOE-DER low emissions turbine program
  - < 5 ppm $NO_x$ (@ 15% $O_2$)
  - Consideration for transition to back-up fuels
  - Durable for at least 8000 hours
  - No more than 10% cost add-on
  - No negative impacts on gas turbine performance
- Develop low-swirl injector for Solar Taurus 70 engine
  - ≈7690 kW (10,310 hp) 16:1 compression ratio
  - 3 – 4 % $\Delta P$
  - Annular liner fitted with 12 injectors

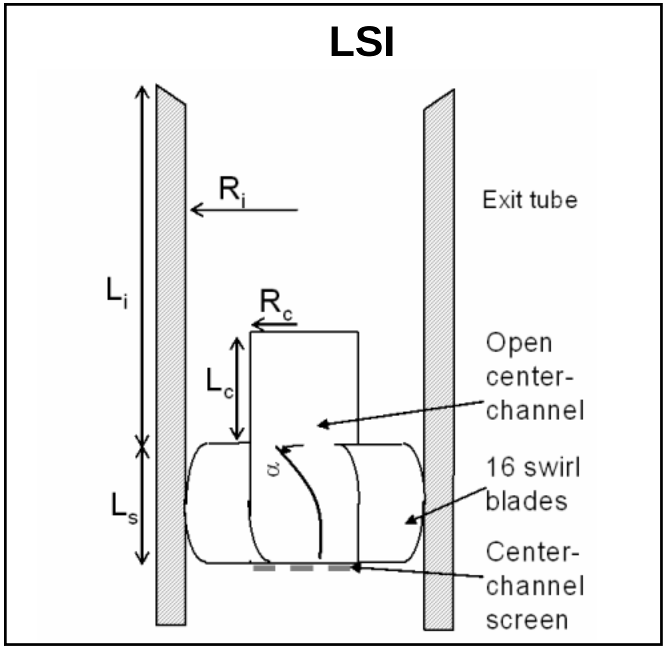


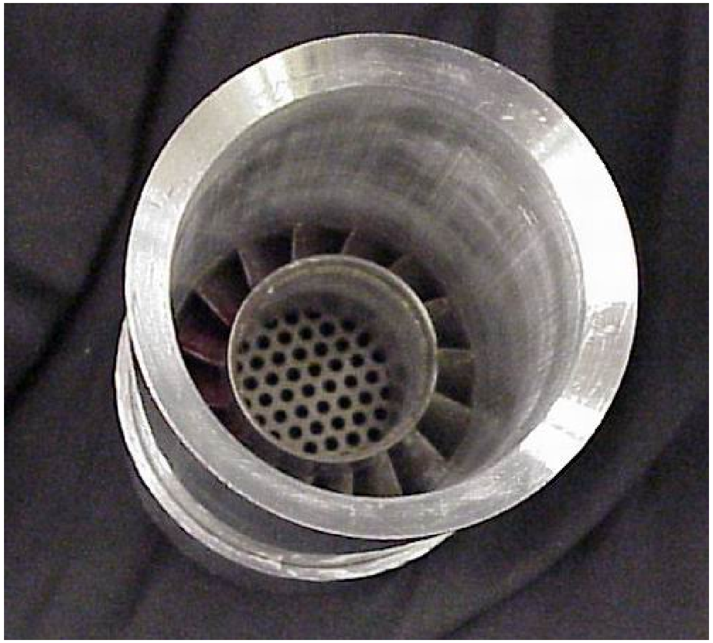
# Developmental Steps of LSI for Solar Taurus 70

- **Laboratory configuration and evaluation**
- **Single injector tests at high temperature and pressures**
- **Development of a fully functional LSI with pilot and premixer**
- **Atmospheric multi-injector tests in annular liner**
- **~~Multi-injector pressurized tests in a developmental loop-engine~~**
- **Engine tests and optimization**

# $1^{st}$ Low-swirl Injector (LSI) Prototype

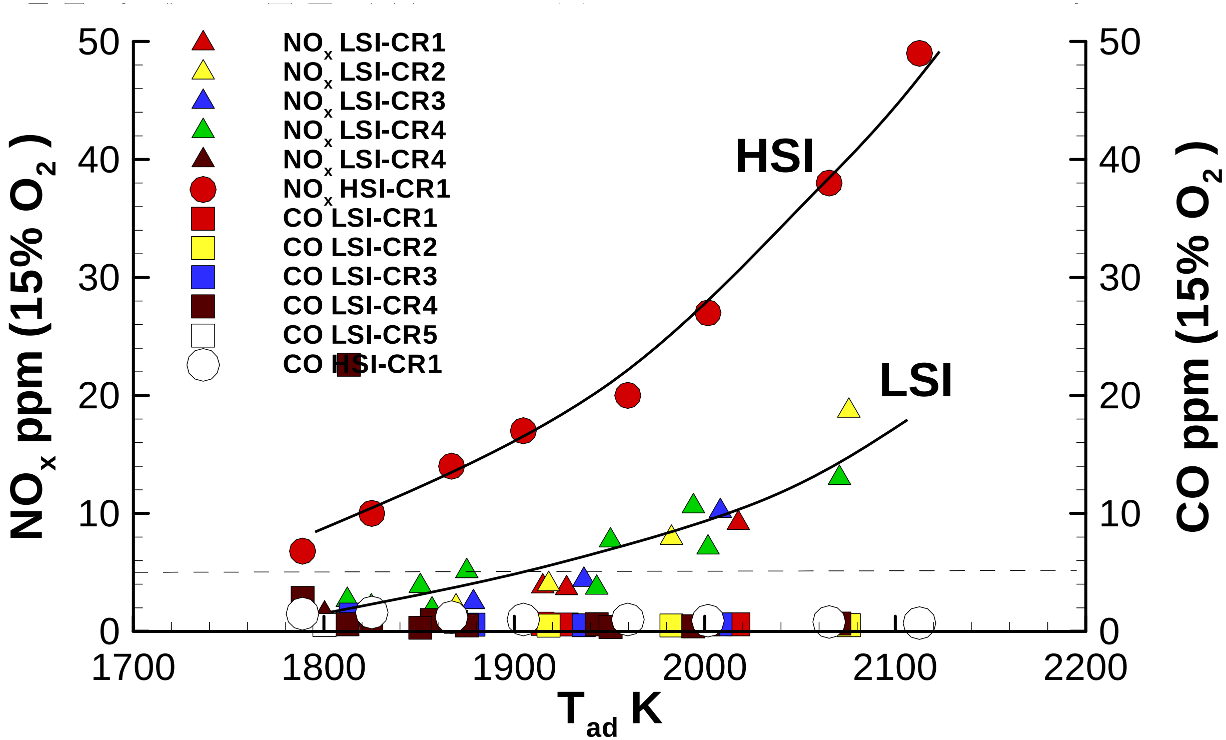
- **Utilize vane swirler for SoLoNOx Taurus 70**
  - **Configured in laboratory at STP and low $U_0$ (8 m/s)**
    - **Replace centerbody with perforated screen (38% open)**
    - **Followed guidelines from industrial burner development**
      - **0.4 < S < 0.55**
      - **1.5 ratio between barrel length (swirler recess) and injector diameter**



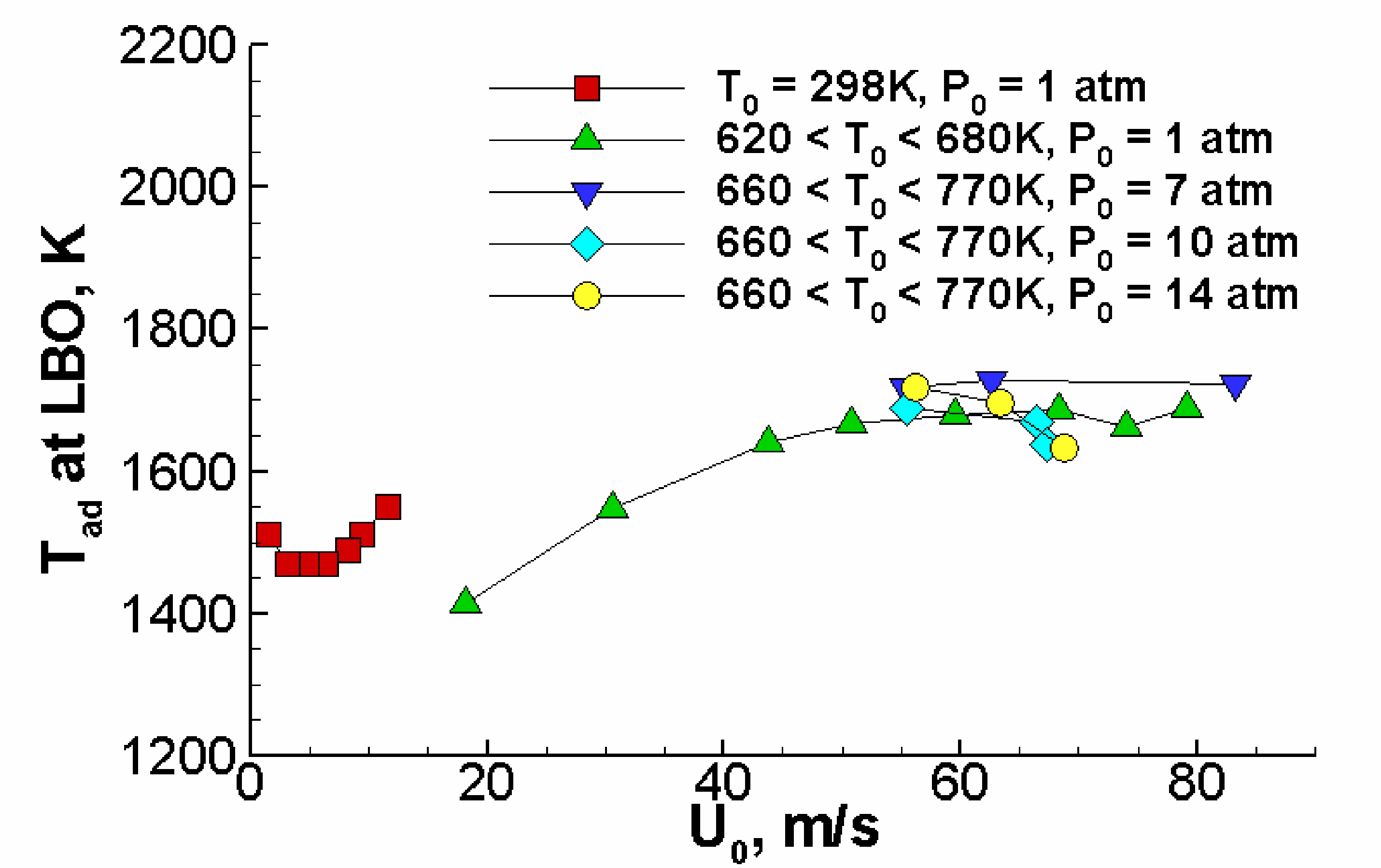
# Single Injector Rig-Test Showed Ultra-Low Emissions

- **Demonstrated low-swirl injector concept at full and partial loads ($500 < T_{in} < 900$F, $5 < P < 14$ atm)**
- **$NO_x$ emissions of LSI 60% lower then conventional DLN high-swirl injectors**
- **CO emissions well below acceptable limit**
- **Emissions same for +/- 10% and +/- 3% premixer**



# LBO of LSI unchanged at velocities up to 60% above design point

- **LBO remains relatively insensitive to bulk flow velocity $U_0$**



# Development of an Engine-ready LSI Prototype

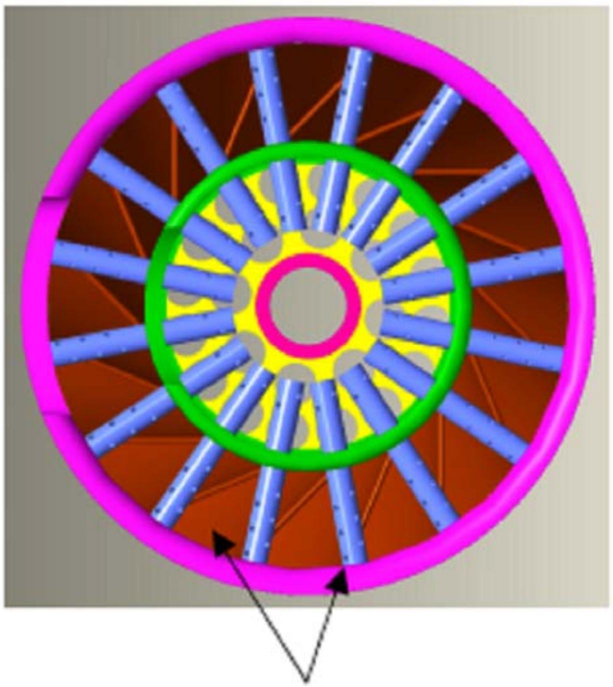
- **Confirm LSI operability within a typical engine cycle**
  - **Design and testing of a fully functional LSI prototype with a premixer and a pilot**
- **Configure the LSI to be "Drop-in" injector to replace SoLoNOx injector for Taurus 70**
  - **Demonstrate engine readiness and low impact on engine performance**
  - **Evaluation criteria**
    - **Operability (light-off, loading & unloading protocol, response to off-design conditions)**
    - **Injector to injector interactions**
    - **Combustion oscillations**
    - **Emissions**

# Integration of a Pilot for LSI

- **Embedded central pilot gives the best performance among several options**
  - **Particle image velocimetry (PIV) measurements to optimize pilot tube size and assess effects on flowfield**
  - **Direct injection of pilot fuel to create a locally richer zone in the central non-swirling region**
  - **Flame burns in premixed mode from ignition to full load**

**LSI-2 with embedded pilot**

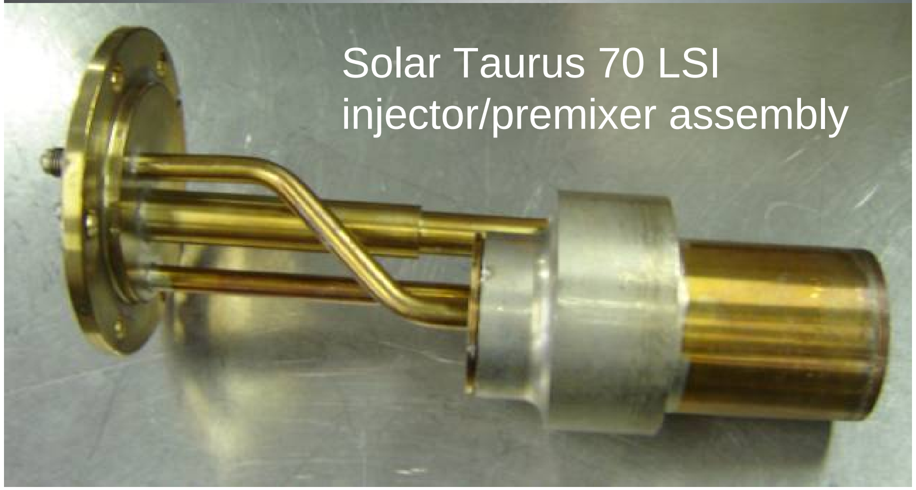
# Configured Simple Premixer



16 axial vanes & fuel spokes

- Similar to SoLoNOx multi-spoke design
  - Longer fuel tubes supplying both center channel and swirl annulus
- Optimize to achieve desired homogeneity
  - Varied the number and location of the injection holes
  - Radial uniformity +/- 20%, circumferential uniformity +/- 5%
- Laboratory experiments (at STP) to verify functionality
  - Comparison of flowfields and flame positions with well mixed cases

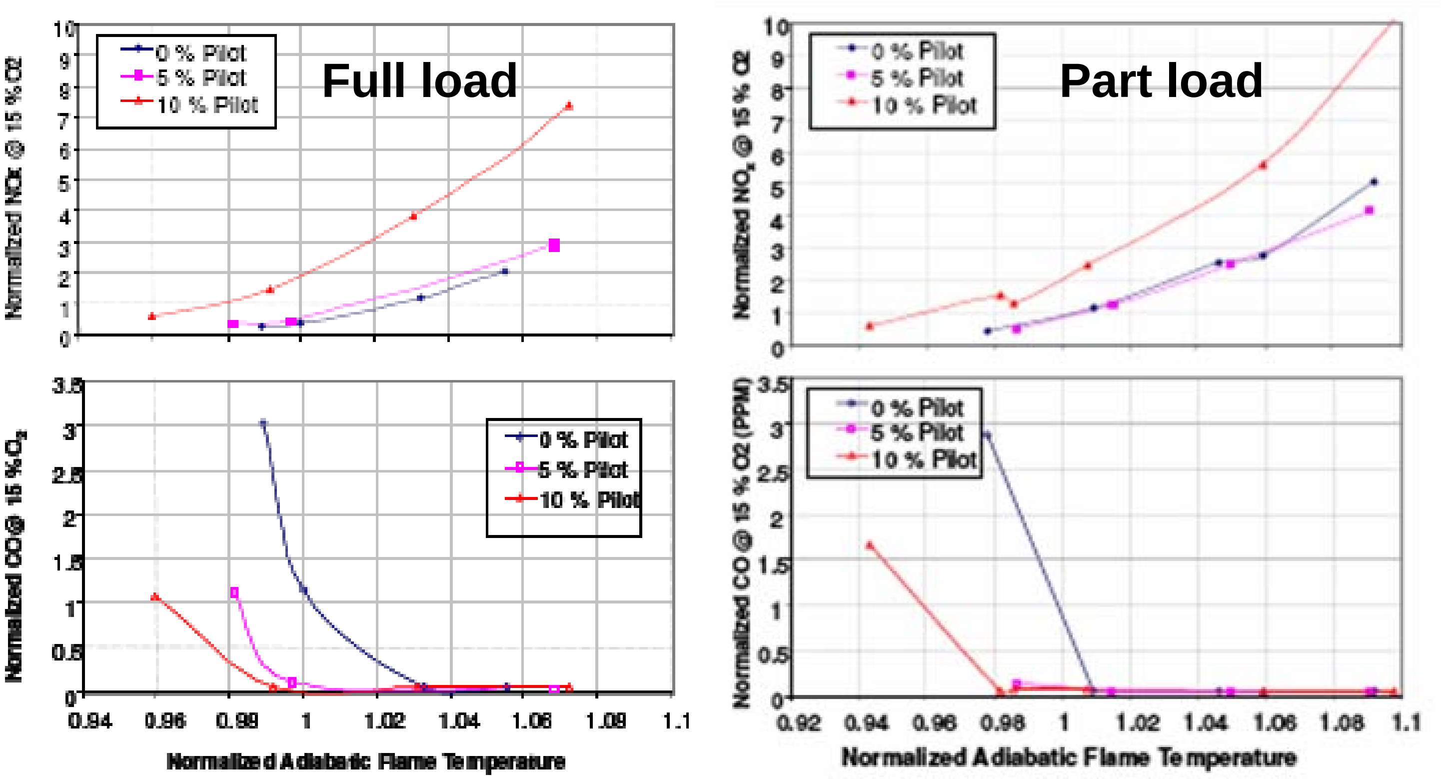
# LSI-3 for Taurus T70

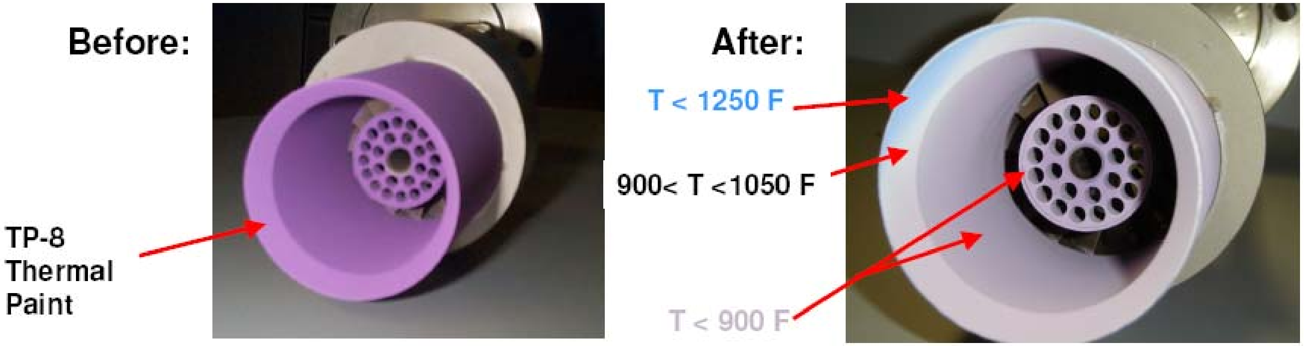

- **LSI-3 built from SoLoNOx swirler**
  - **Significant savings in engineering and fabrication**
- **Same overall size and mounting configuration as T70 SoLoNOx injector**
- **Built 15 injectors**
  - **Selected two at random for baseline performance tests**
  - **12 used for engine test**

# Baseline Performance of LSI-3 from Single Injector Tests

- 5% pilot offers ultra-low $NO_x$ and extends LBO
- $NO_x$ < 2.5 ppm
- CO well below acceptable levels
- 30% pilot further extends LBO

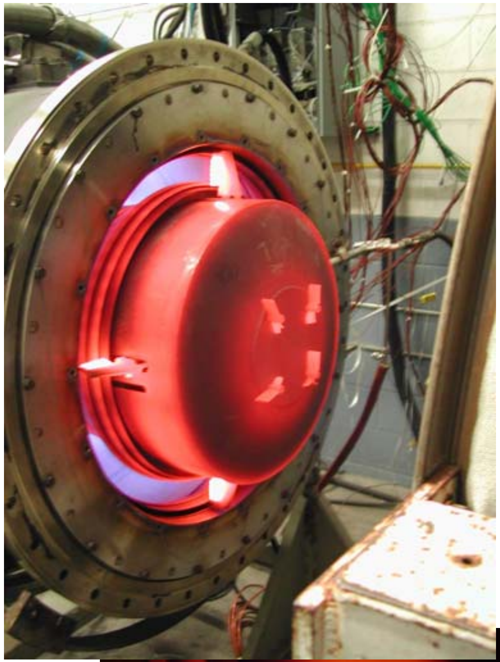


# LSI Does Not Experience Significant Material Heating Due to Lifted Flame



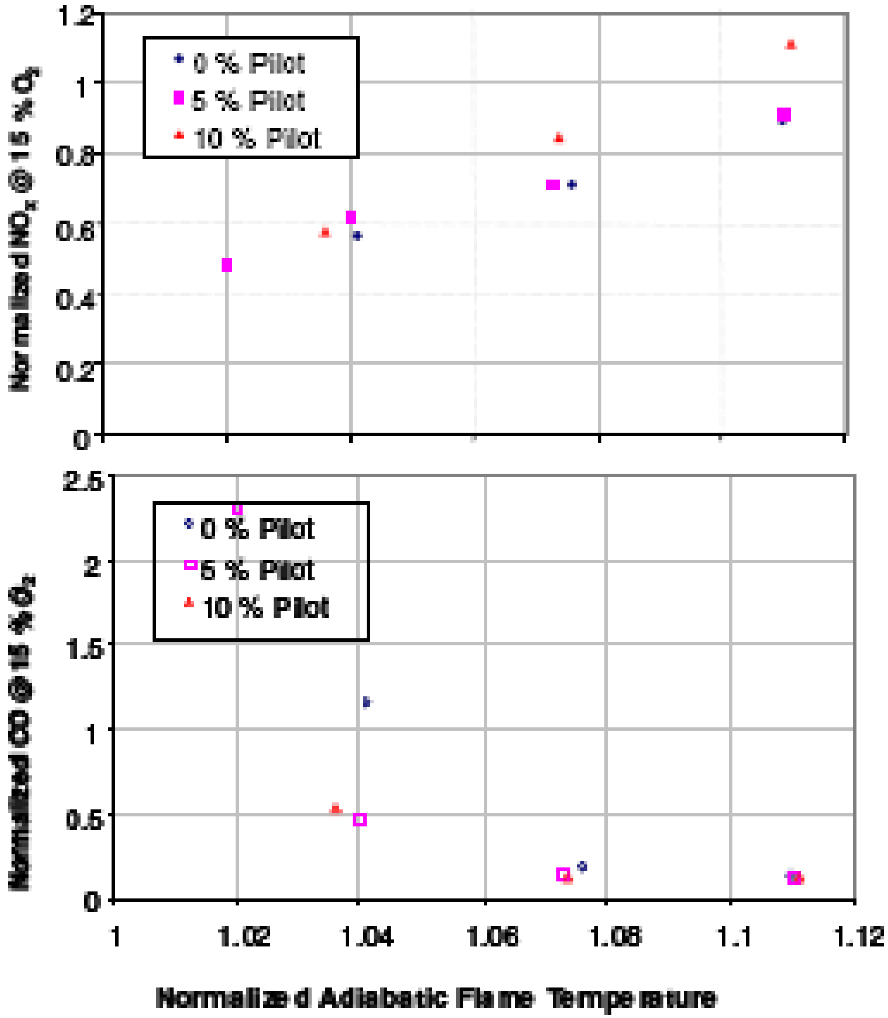

- **Temperature sensitive paint tests of LSI-3 show most regions experience temperatures below 915F for $T_0$ = 800F**
- **Represents a major benefit of the technology**
  - **Maintaining low material temperature without requiring active cooling**
  - **prolong service life**

# Multi-Injectors Atmospheric Annular Liner Tests



- 12 LSI-3 fitted to a T70 annular liner and evaluated at simulated partial and full load with 0, 5 and 10% pilot.
- Circumferential and radial temperature distributions were within the acceptable limits
- LSI-3 showed excellent light-around characteristics with no indication of combustion harmonics or injector to injector interactions

# LSI-3 Emissions in Atmospheric Annular Liner




- **Trends similar to single injector tests**
- **Skipped testing in developmental loop engine and proceed directly to engine tests**
- **1st round of LSI-3 tests in T70 engine complete June 2006**
  - **Engine $NO_x$ emissions identical to rig test results**

# LSI Meeting Metrics of DOE-DER Low Emissions Turbine Program

- **Robust technology offering significant savings in development, fabrication, operating and maintenance costs**
  - **Simple scalable design built from existing parts**
  - **Configure by laboratory experiments without invoking extensive CFD design iterations**
  - **No special requirements for materials and control**
  - **Lifted flame induces minimal thermal stresses & metal fatique**
- **Exceptional performance**
  - **$NO_x$ < 5 ppm at $T_{PZ}$ away from blowoff**
  - **No flame shift or flashback with load change**
  - **Flame robust to withstand large swing in inlet conditions**
  - **Vulnerability to oscillations no different than SoLoNOx**
  - **Emissions not sensitive to small degree of mixture inhomogeneity**
  - **Lower $\Delta P$ for potential efficiency improvement**

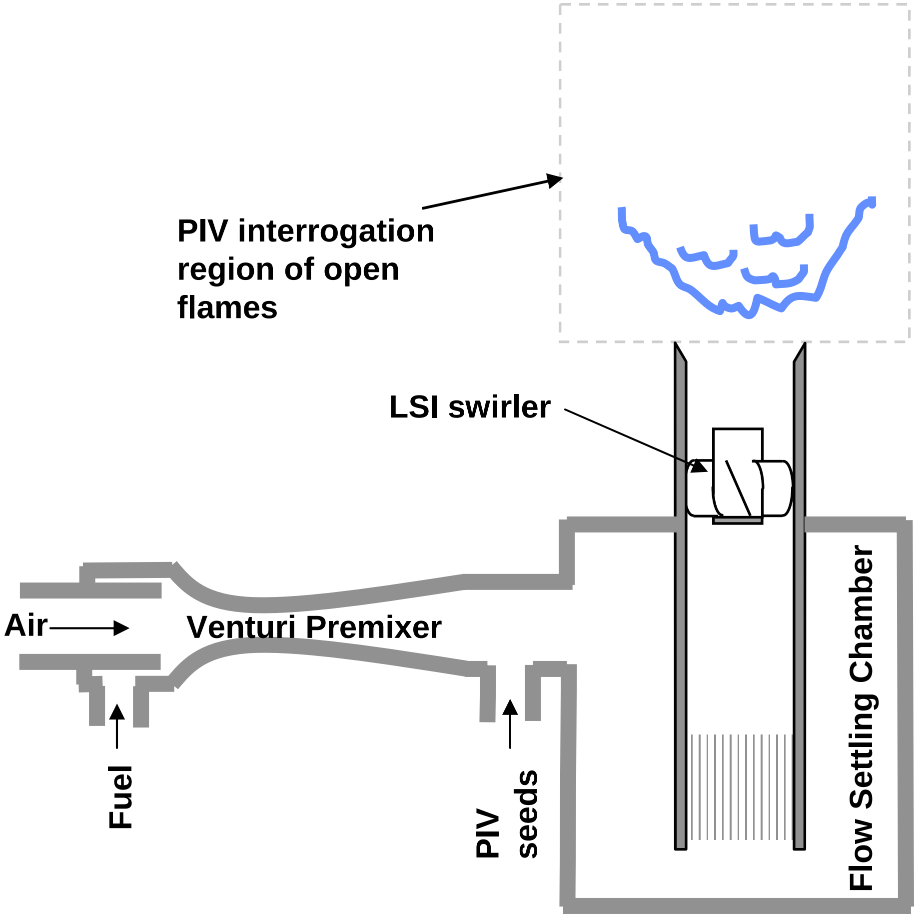
# Part 3

## LSC adaptation to large scale turbines for natural gas, syngas, and hydrogen fuels

# Obtaining an Analytical Model for Low-swirl Combustion

- **Apply Particle Imaging Velocimetry (PIV) to measure instantaneous velocity vectors within an area of 13 x 13 cm**
  - **Facilitates the collection of a large amount of flowfield data**
- **Characterize flowfield and flame behavior as function of:**
  - **swirl number**
  - **fuel type**
  - **fuel air ratio**
  - **bulk flow velocity**
- **Define key parameters that characterize the flowfield**
- **Develop analytical model for the relationships between the flame and flowfield**
  - **Basis for scaling and adaptation guidelines**
  - **Less reliance on computational fluid mechanics (CFD)**
  - **Reduce uncertainties and increase predictability**

# Apparatus, Diagnostics & Analysis

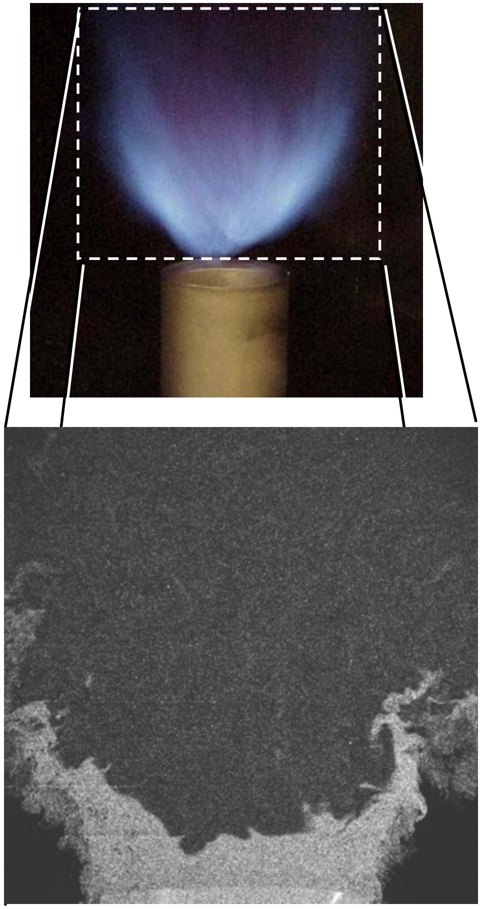



- LSI mounted to the plenum and premixer of an industrial burner
- Applied PIV to atmospheric open flames
  - Previous development with Solar demonstrated relevancy of open flame experiments
- Deduced mean, rms velocities, Reynolds stresses & turbulent flame speeds

# Experimental Conditions

- Lean flames burning single and dual-component fuels with a range of Wobbe indices
- Operating regimes for each fuel defined by LBO and emissions
- Varied bulk flow velocity $U_0$ from 7 to 22 m/s

| Fuel Composition | $T_{ad}$ at $\phi = 1$ K | $S_L$ at $\phi = 1$ m/s | $S_L$ at $T_{ad}$ = 1800K |
|---|---|---|---|
| $CH_4$ | 2230 | 0.39 | 0.17 |
| $C_2H_4$ | 2373 | 0.74 | 0.23 |
| $C_3H_8$ | 2253 | 0.45 | 0.22 |
| 0.5 $CH_4$/ 0.5 $CO_2$ | 2013 | 0.20 | 0.12 |
| 0.6 $CH_4$/ 0.4 $N_2$ | 2133 | 0.31 | 0.16 |
| 0.6 $CH_4$/ 0.4 $H_2$ | 2258 | 0.57 | 0.22 |
| $H_2$ | 2535 | 2.4 | 0.61 |
| 0.5 $H_2$/ 0.5 $N_2$ | 2056 | 1.2 | 0.61 |

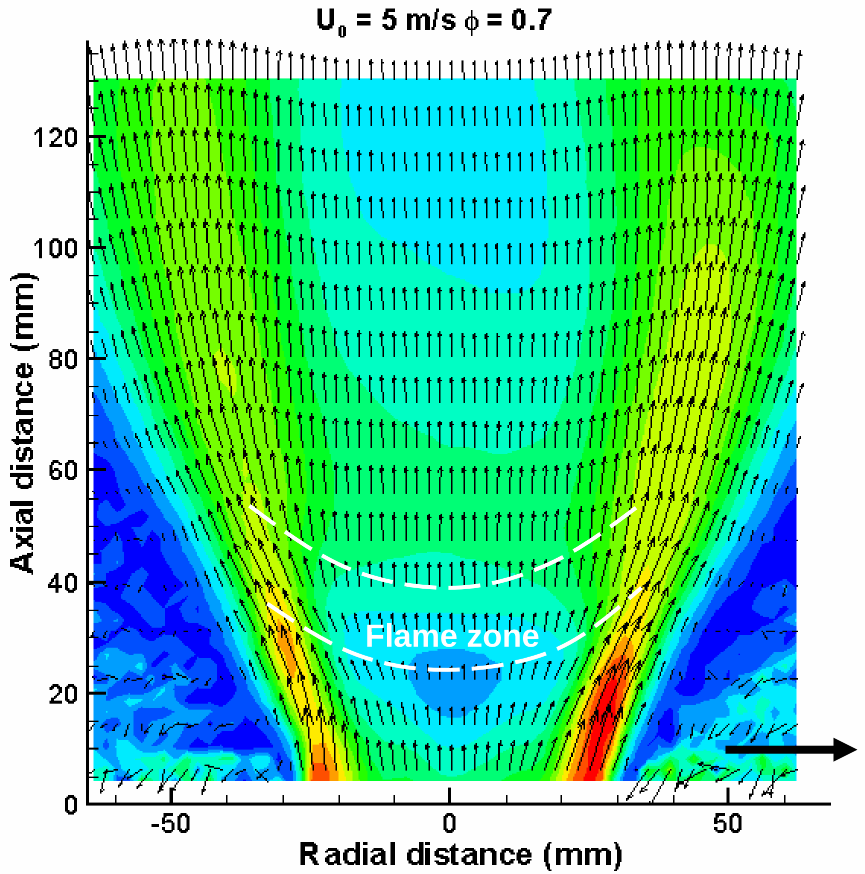


Raw PIV image showing wrinkled premixed turbulent flame structures

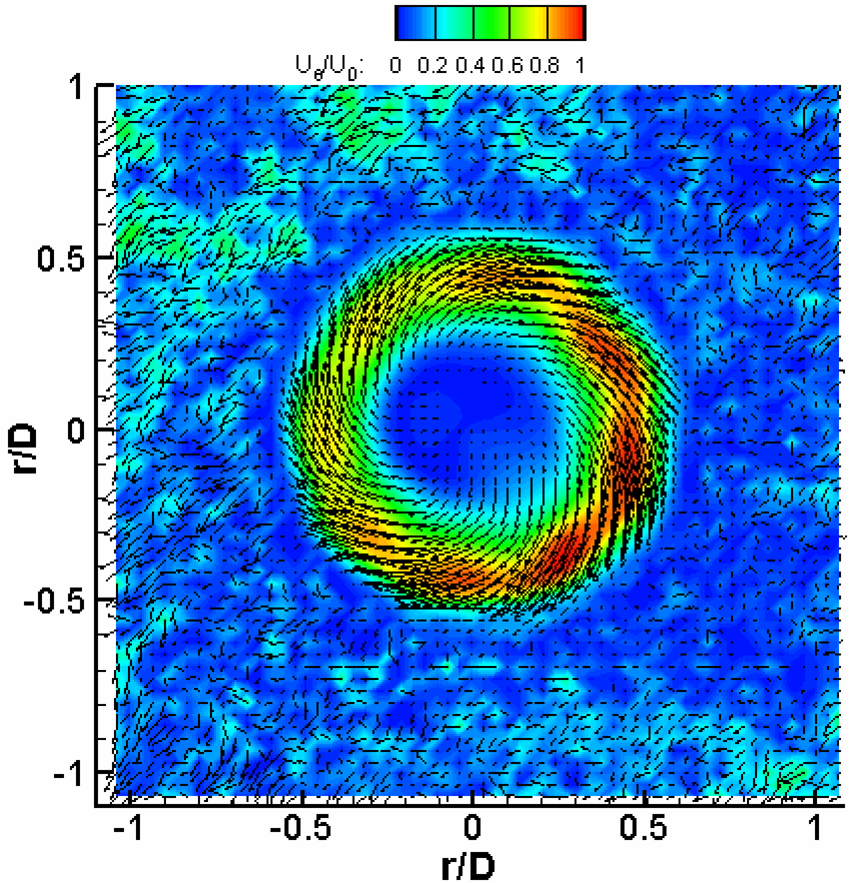
# Hydrocarbon Flame Results

# Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**

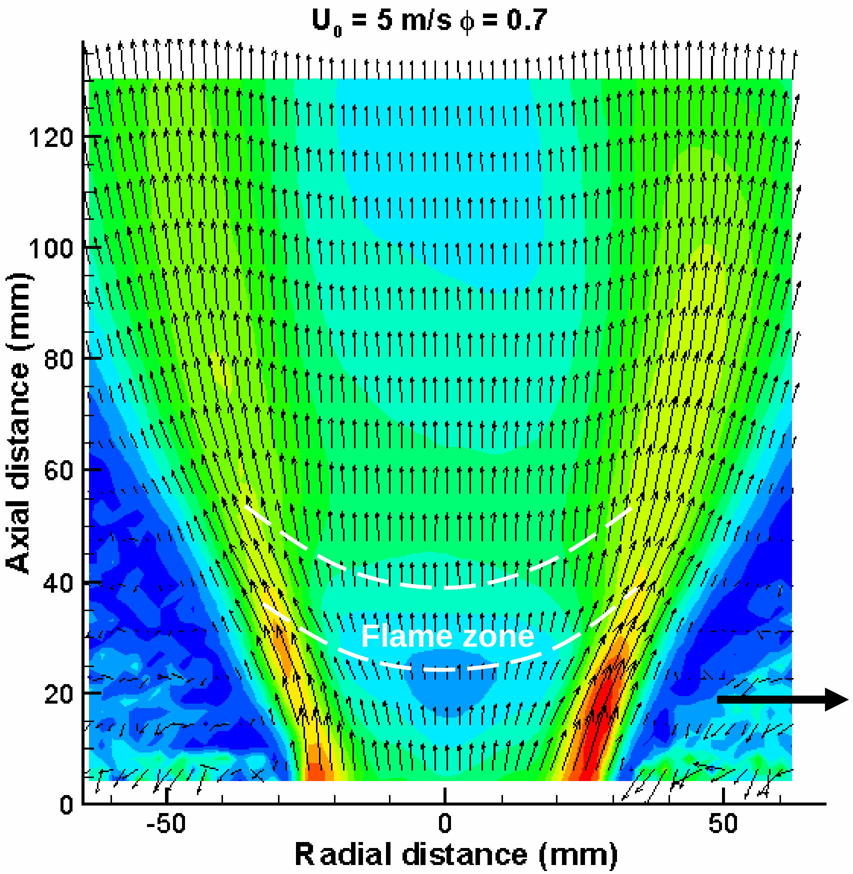


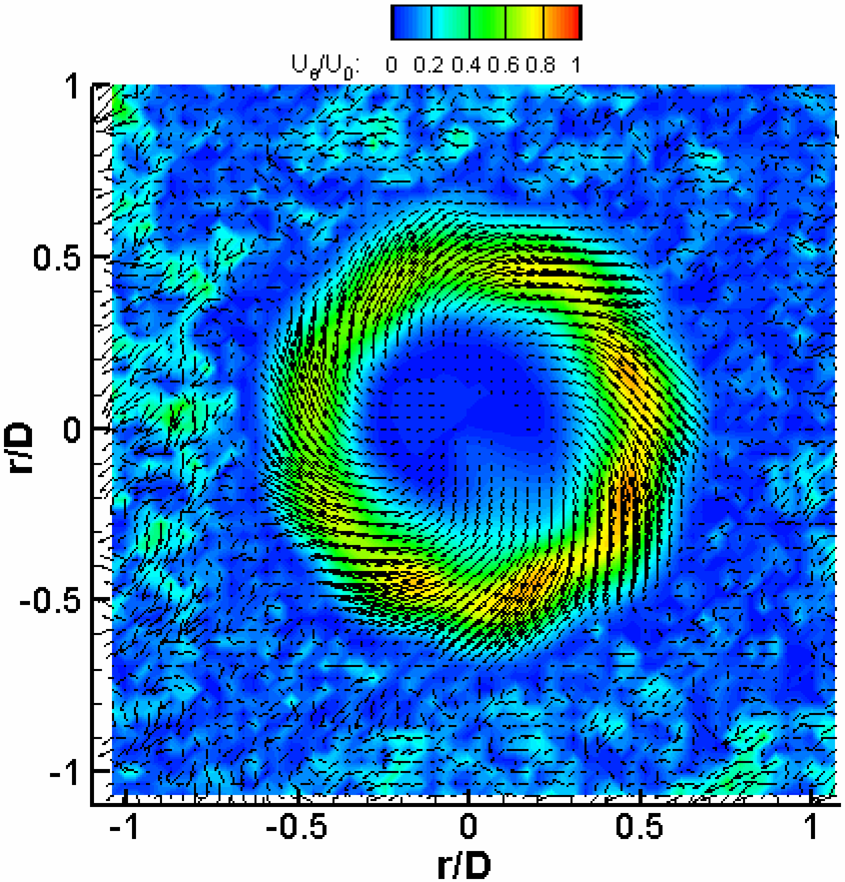

- **Mean velocity vectors on cross-plane**



# Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**
- **Mean velocity vectors on cross-plane**



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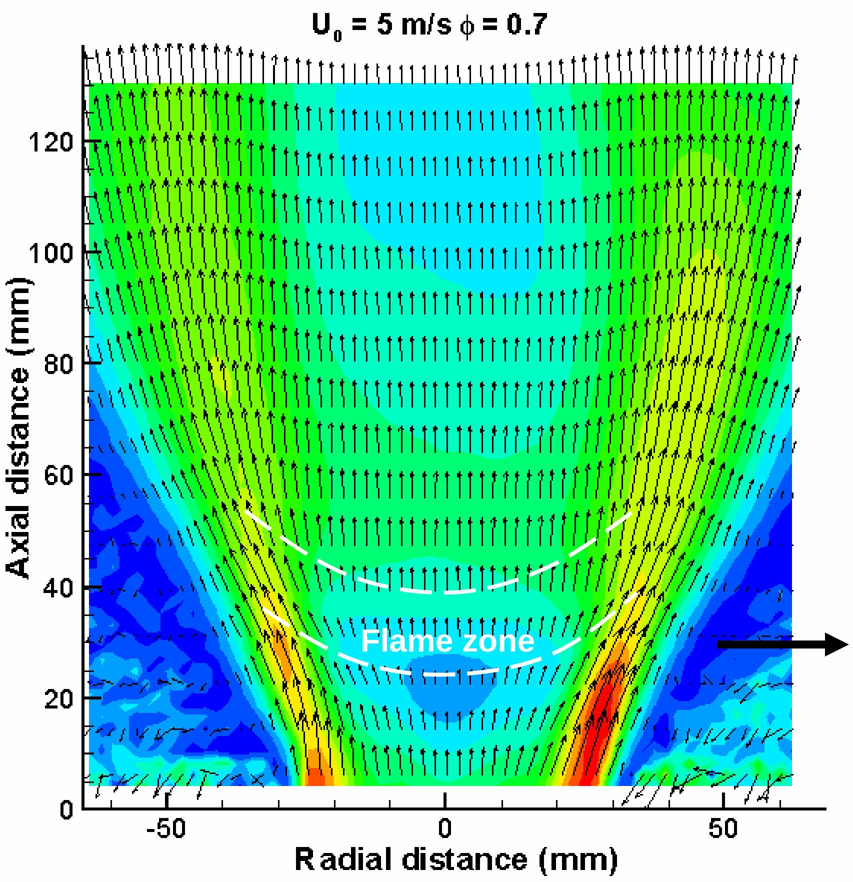
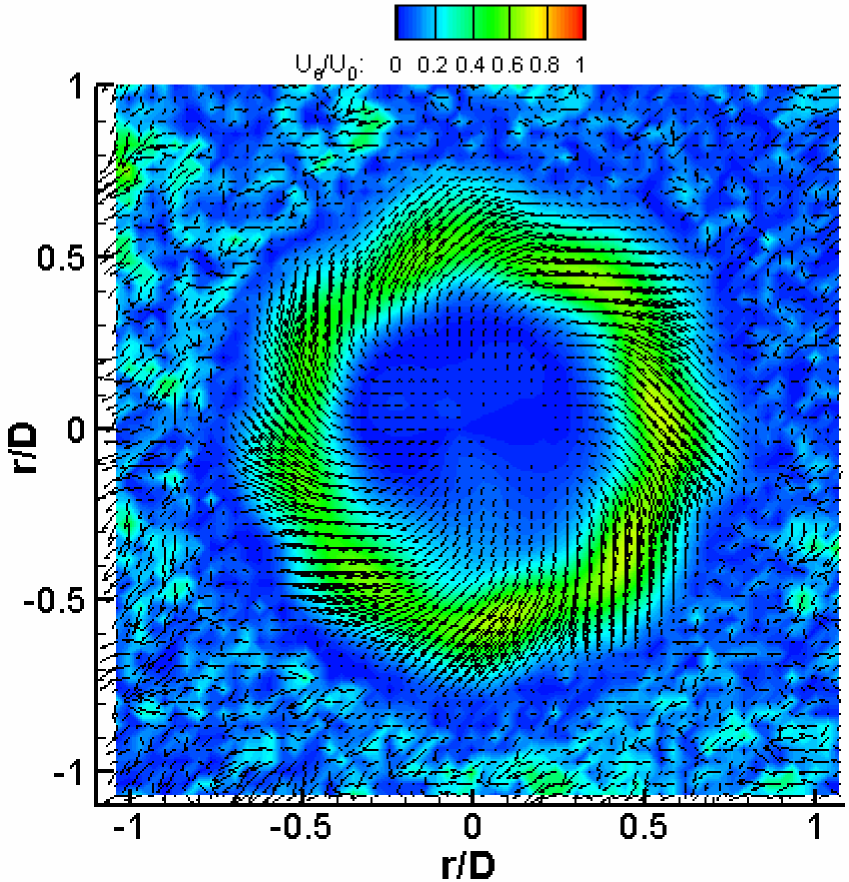



- **Mean velocity vectors on cross-plane**



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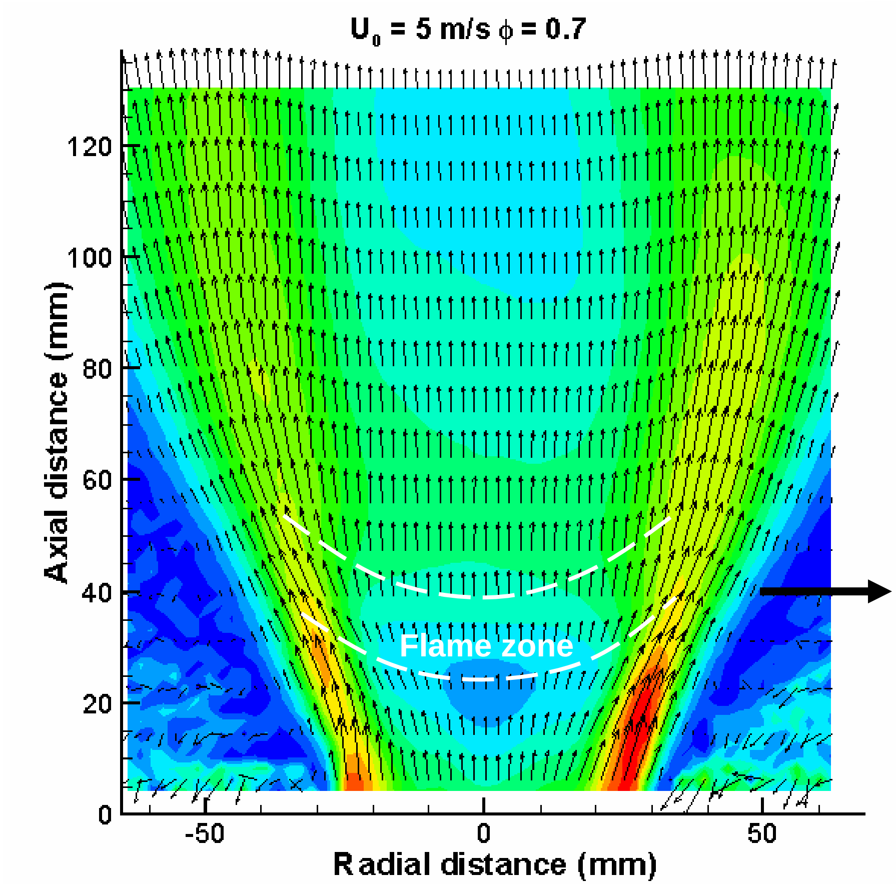
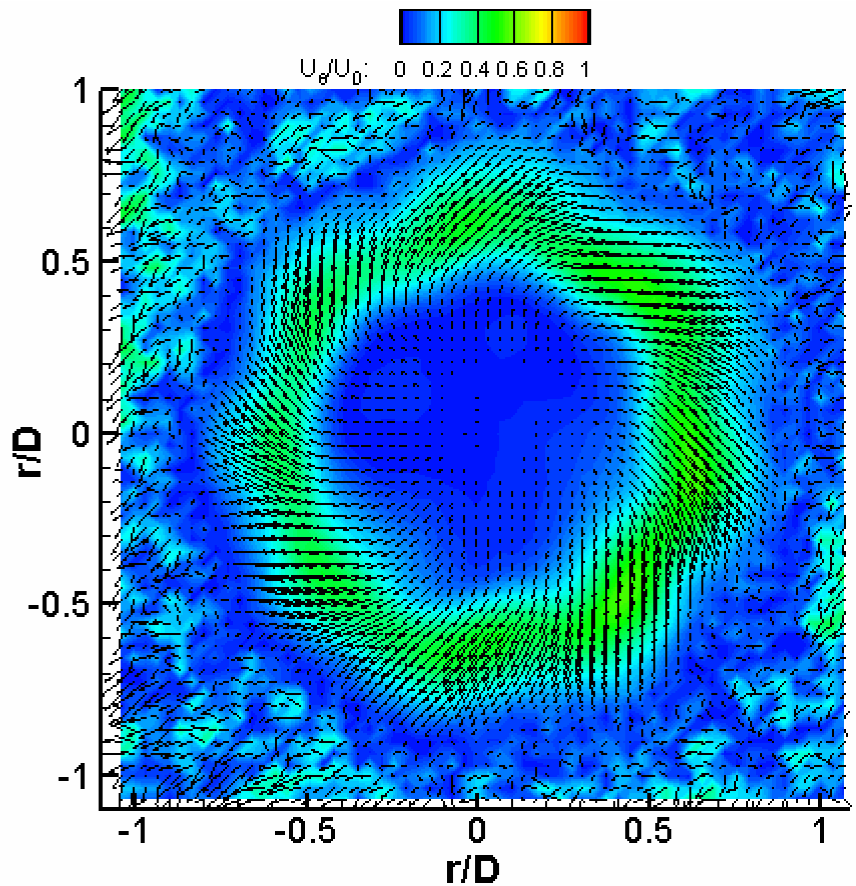



- **Mean velocity vectors on cross-plane**



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- **Mean velocity vectors on axial plane**
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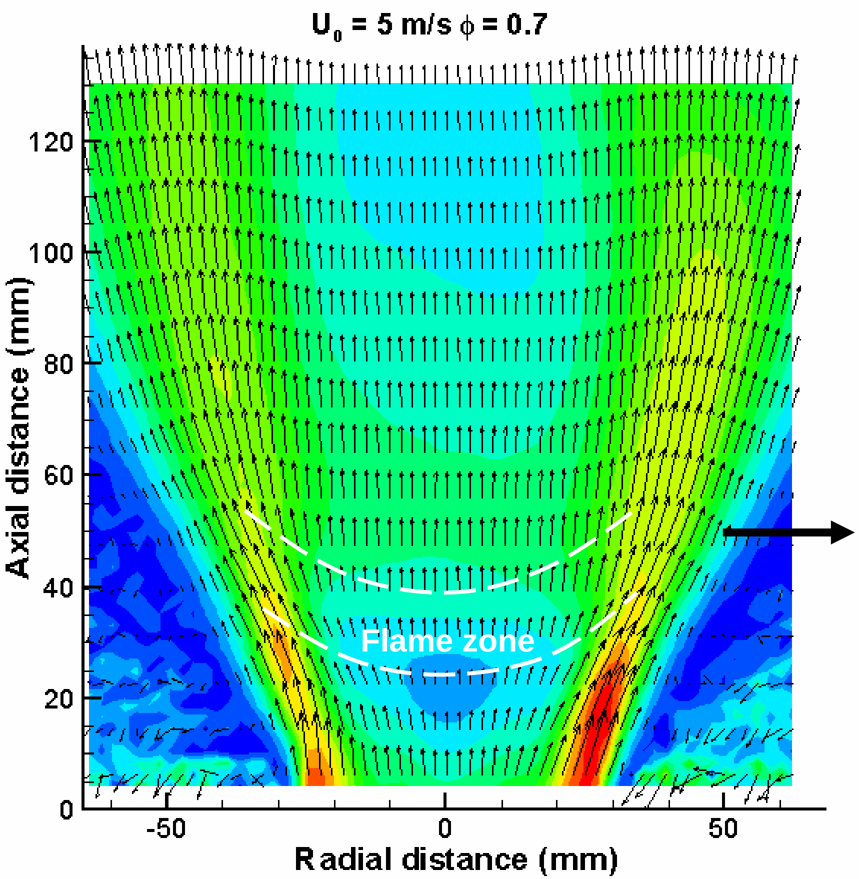
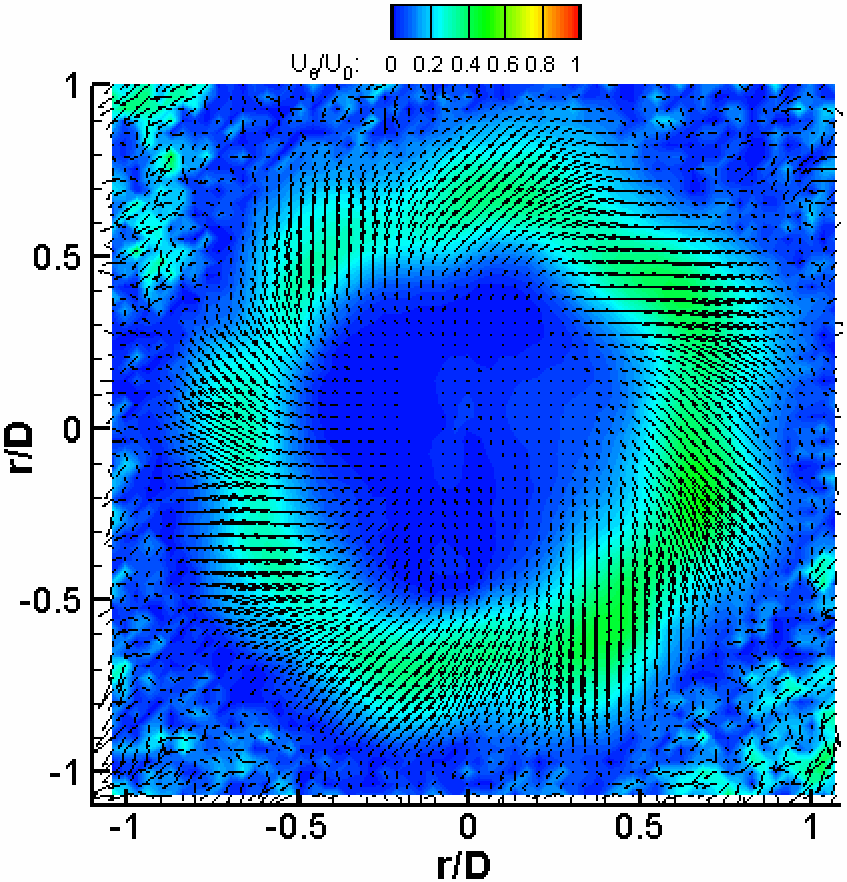
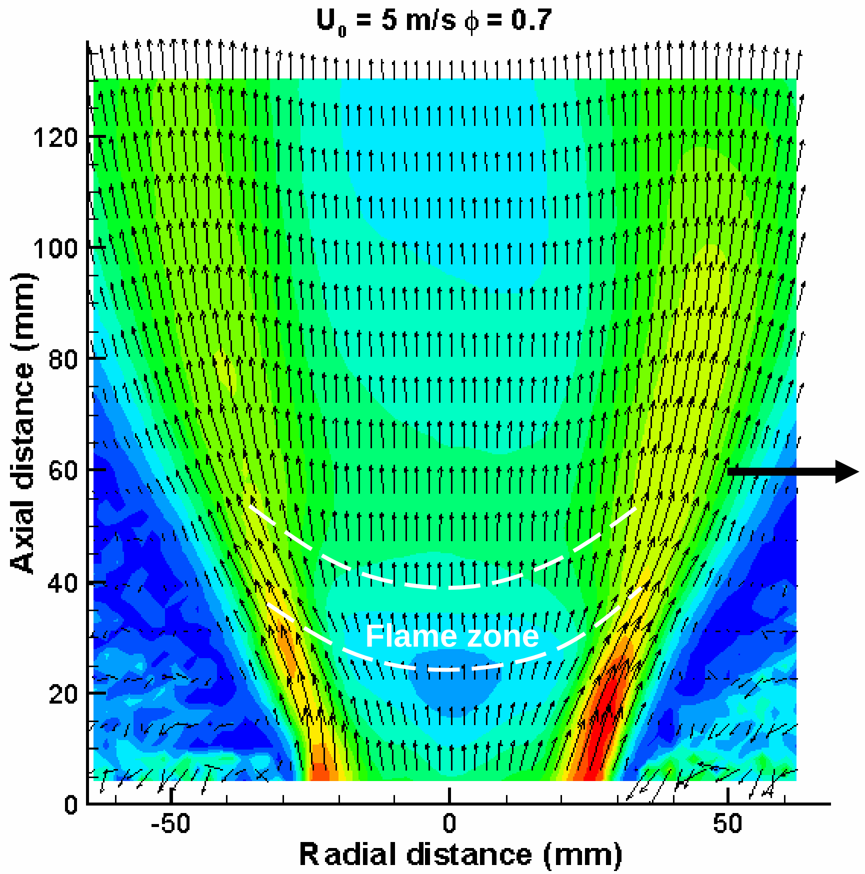


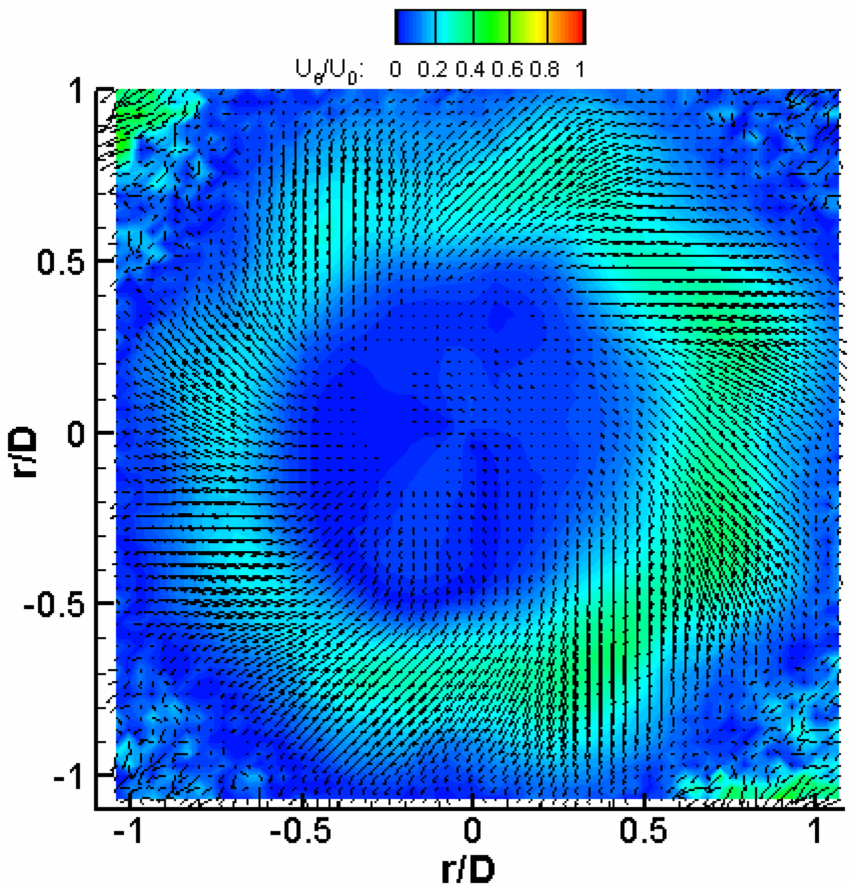



# Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**

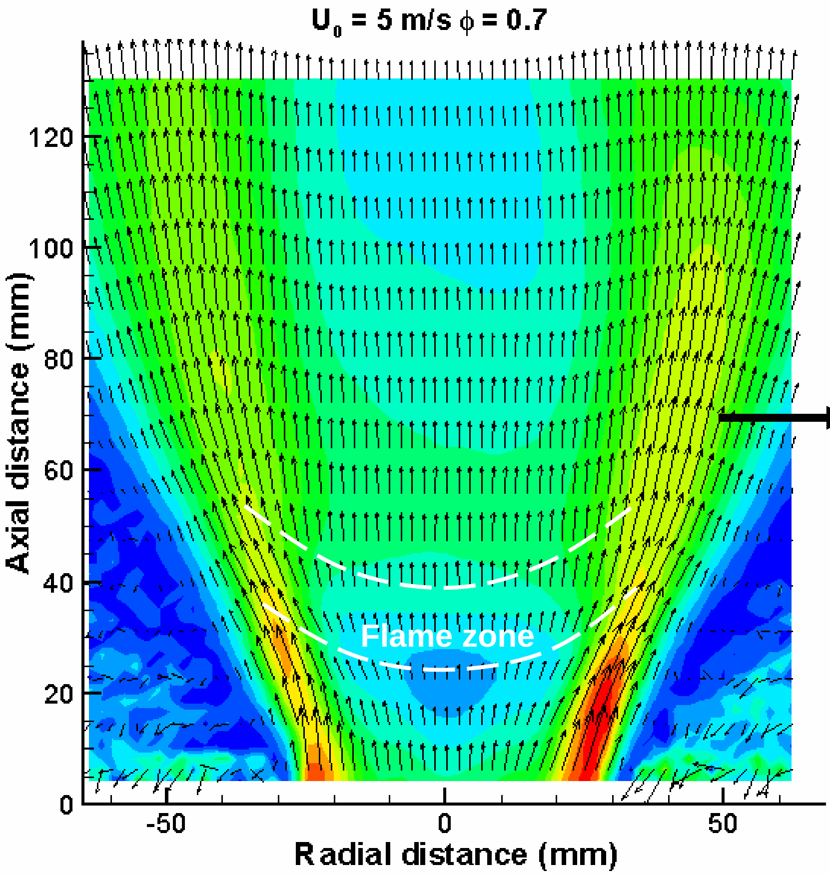


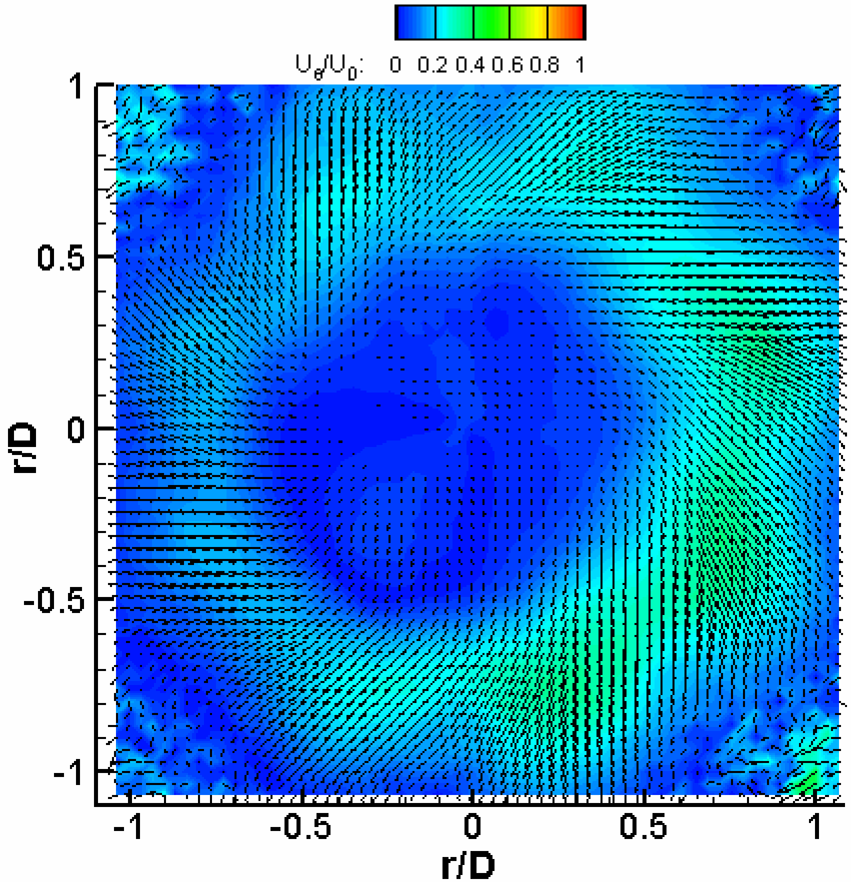

- **Mean velocity vectors on cross-plane**



# Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**
- **Mean velocity vectors on cross-plane**



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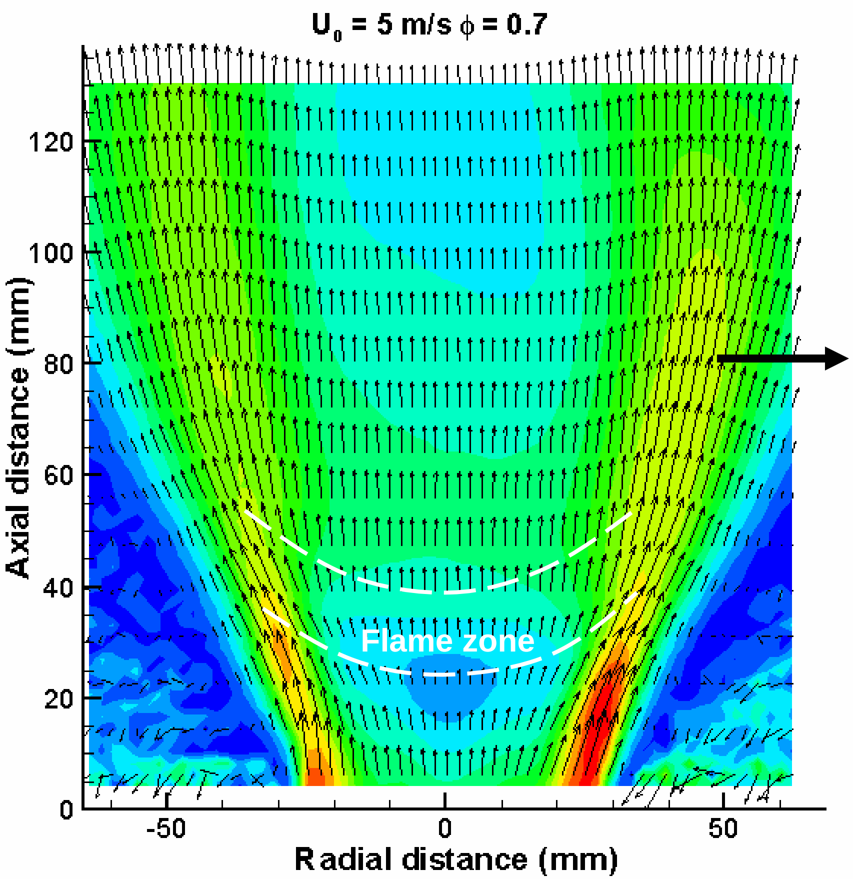


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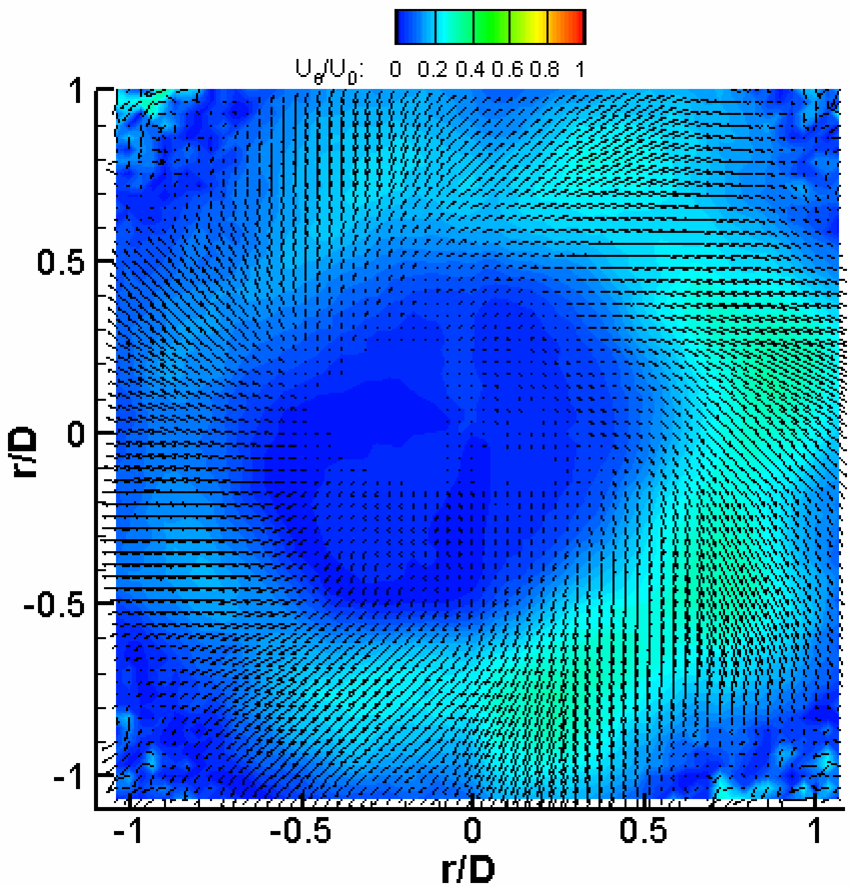
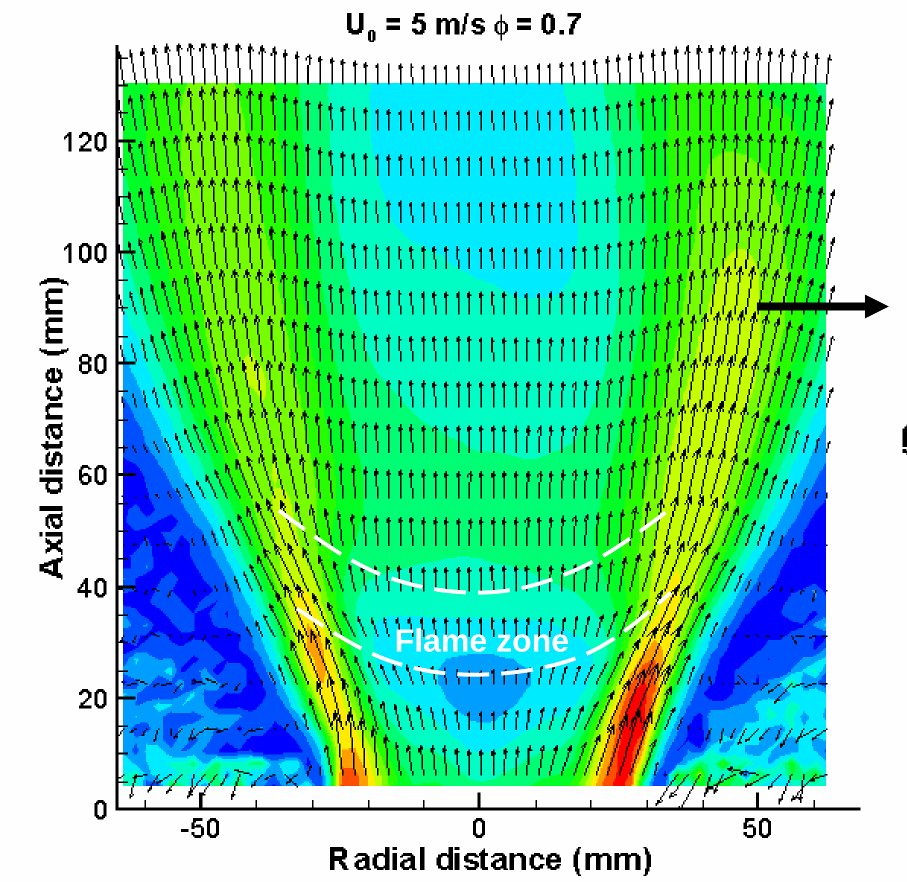
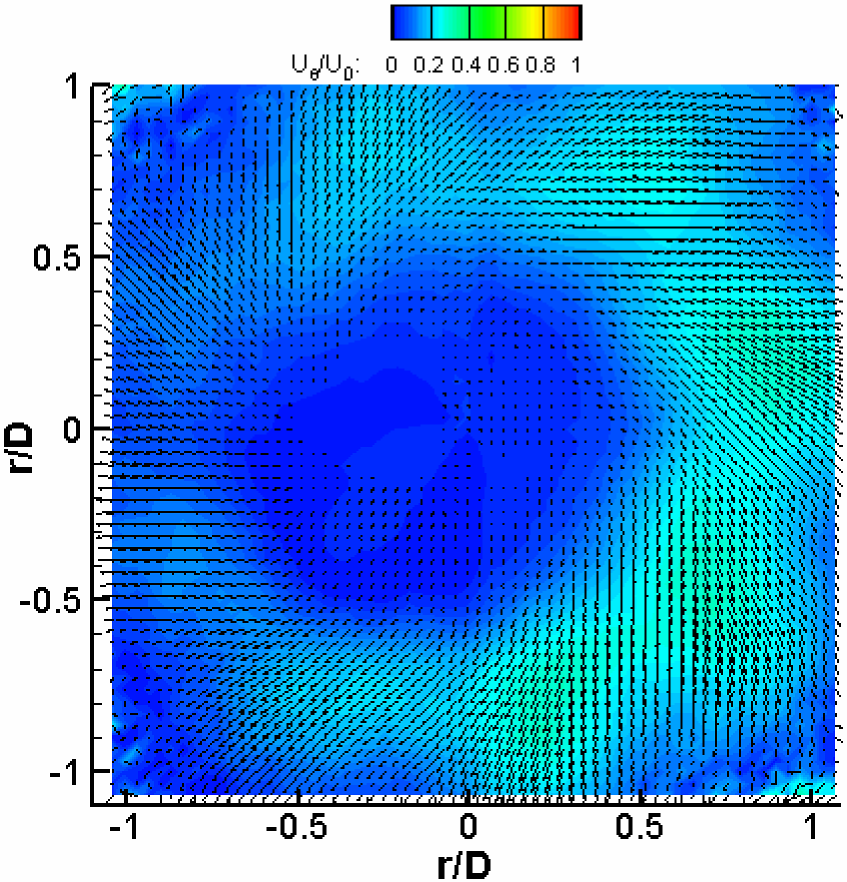


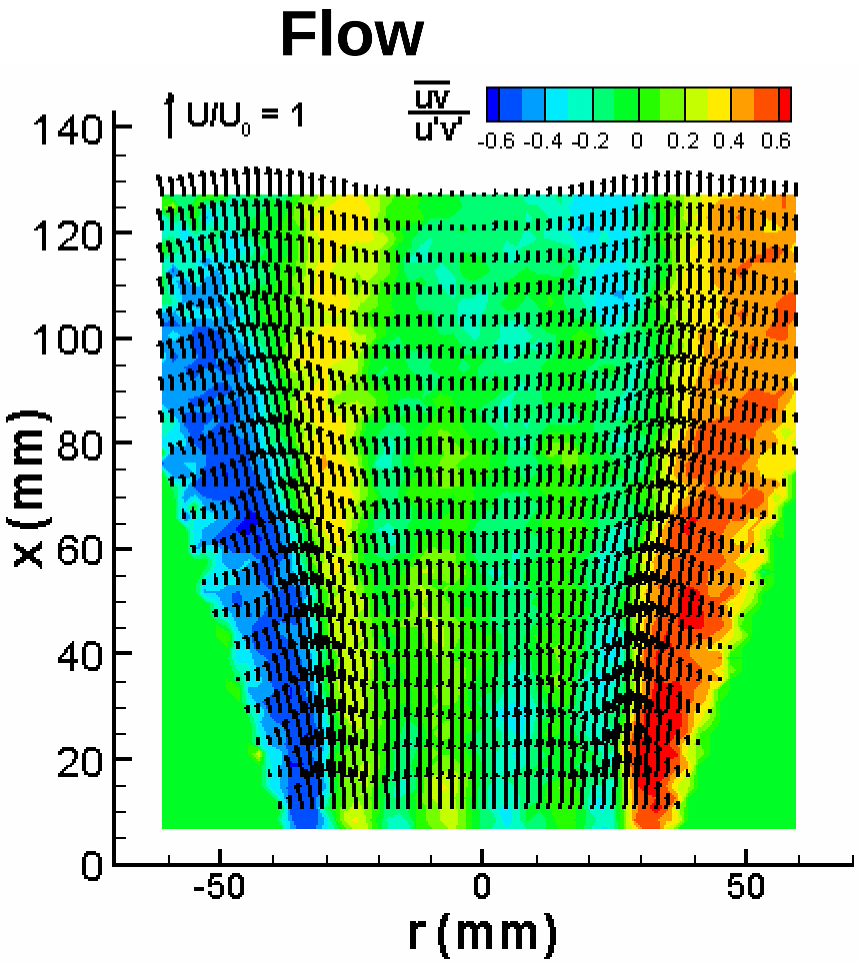
# Flowfield of LSC Shown by Particle Image Velocimetry

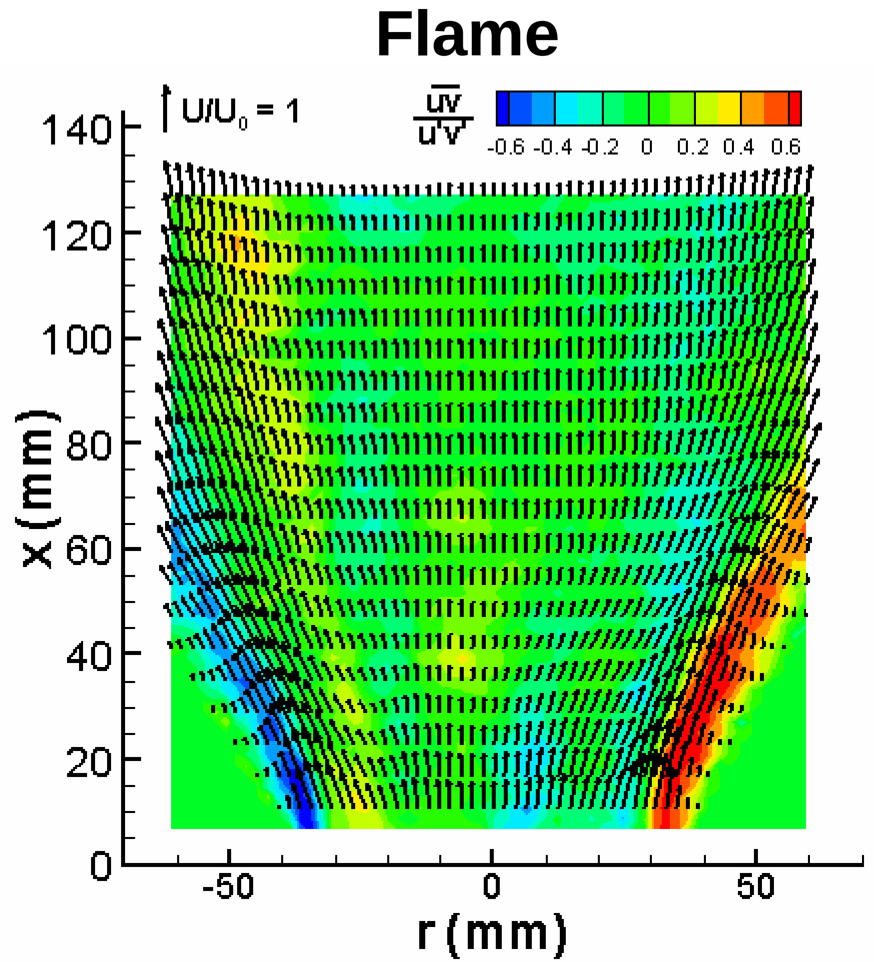
- **Mean velocity vectors on axial plane**
- **Mean velocity vectors on cross-plane**



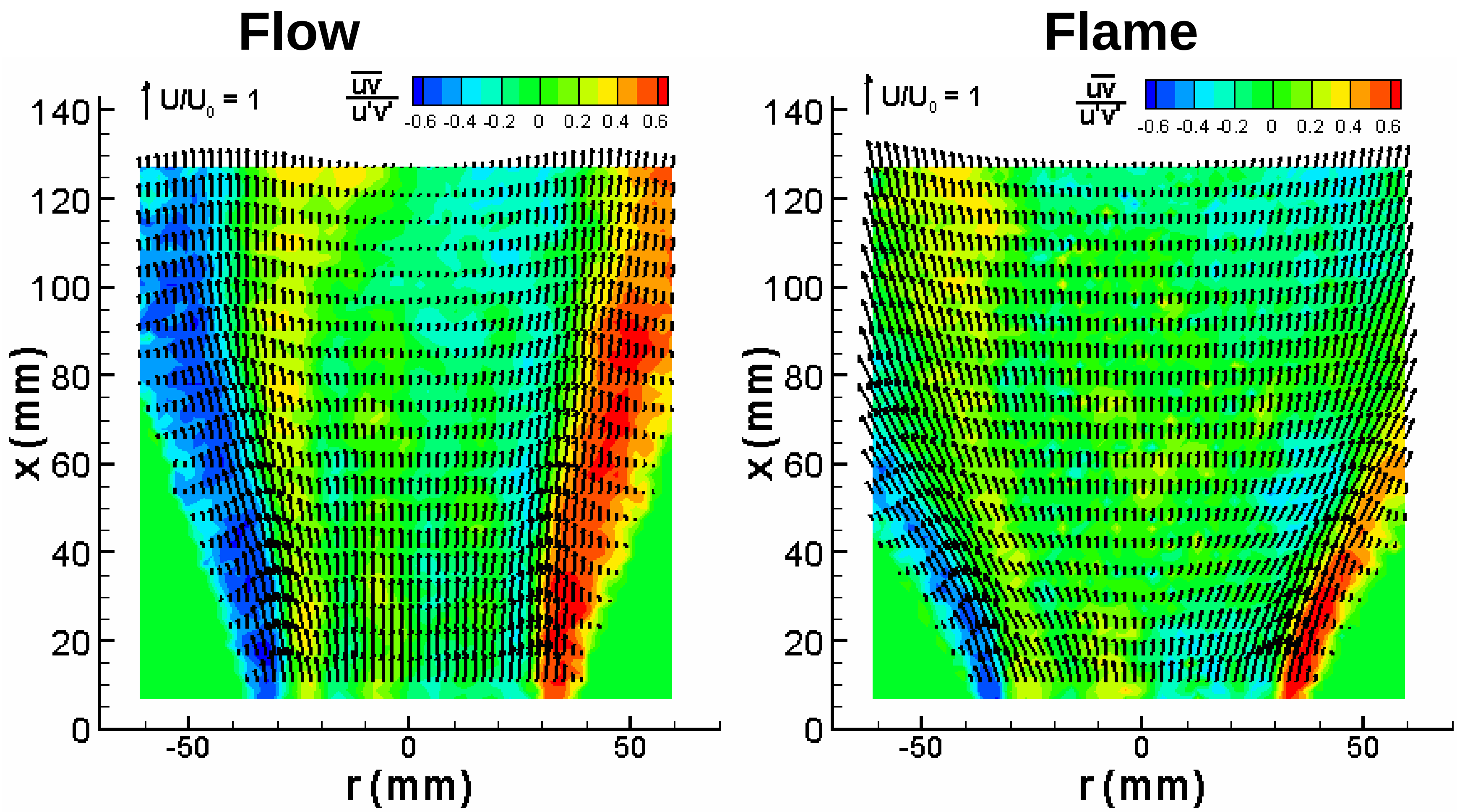



# Normalized mean vectors and Reynolds stress at $U_0$ = 7 m/s

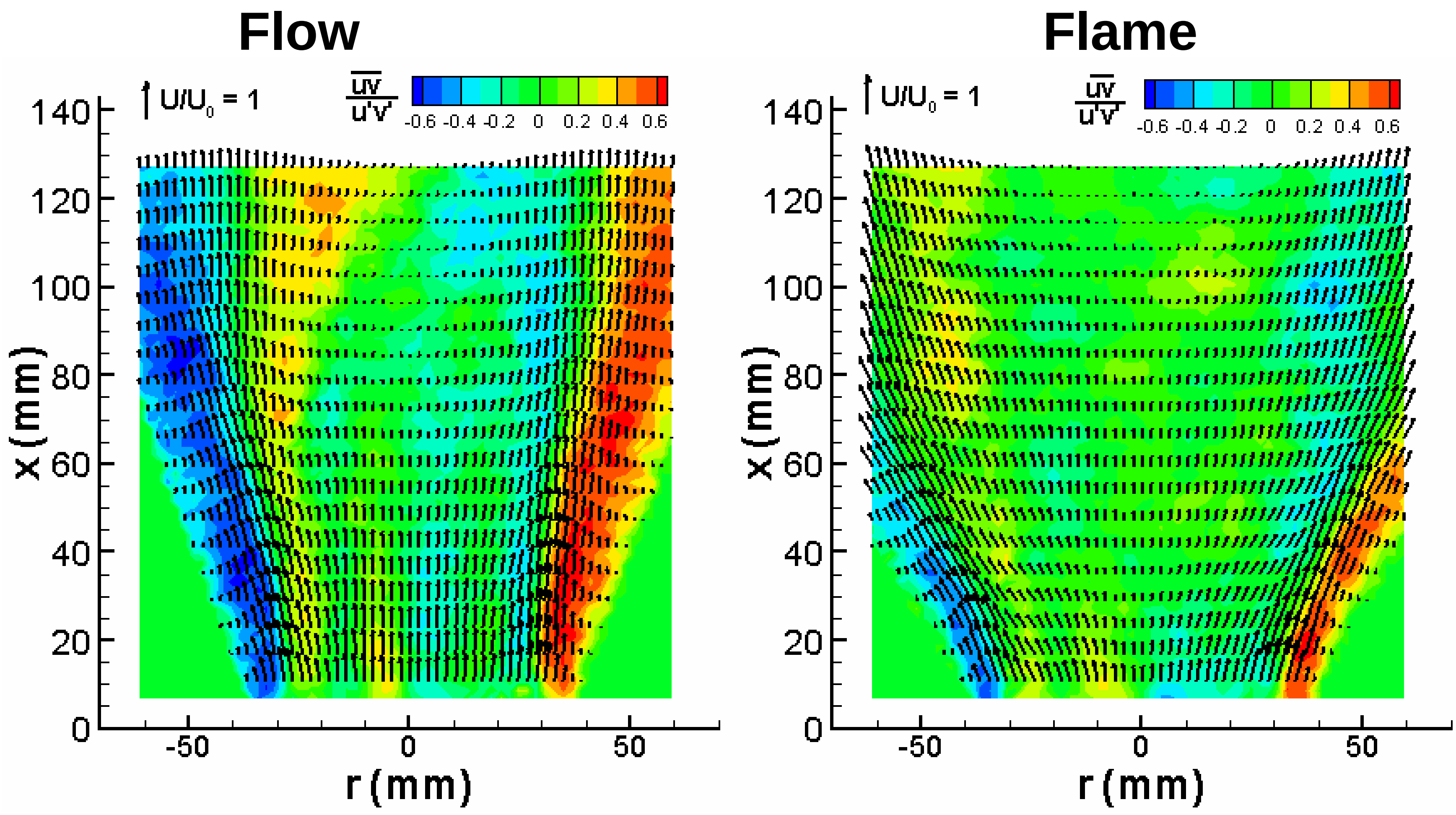


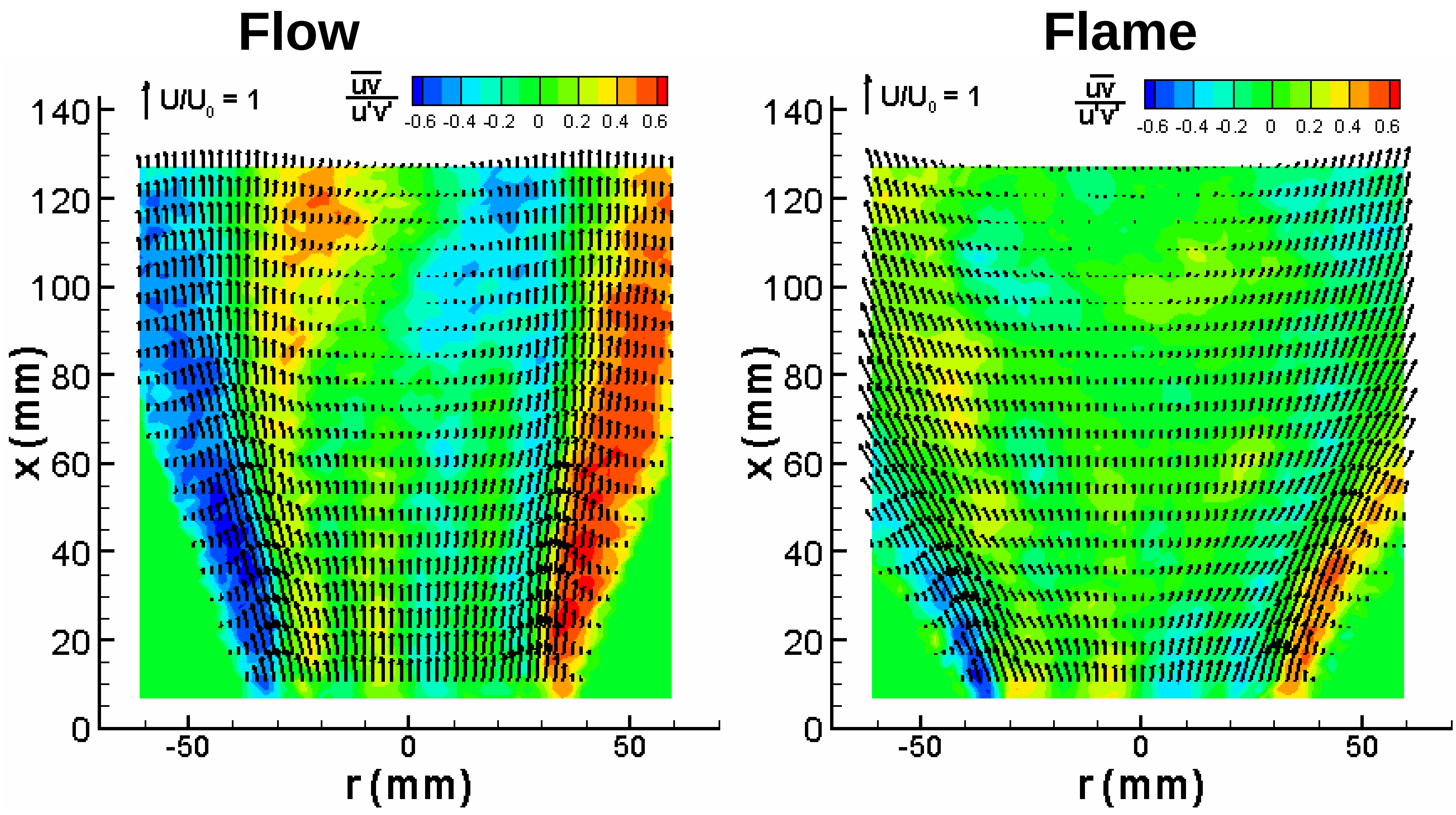
# Normalized mean vectors and Reynolds stress at $U_0$ = 10 m/s



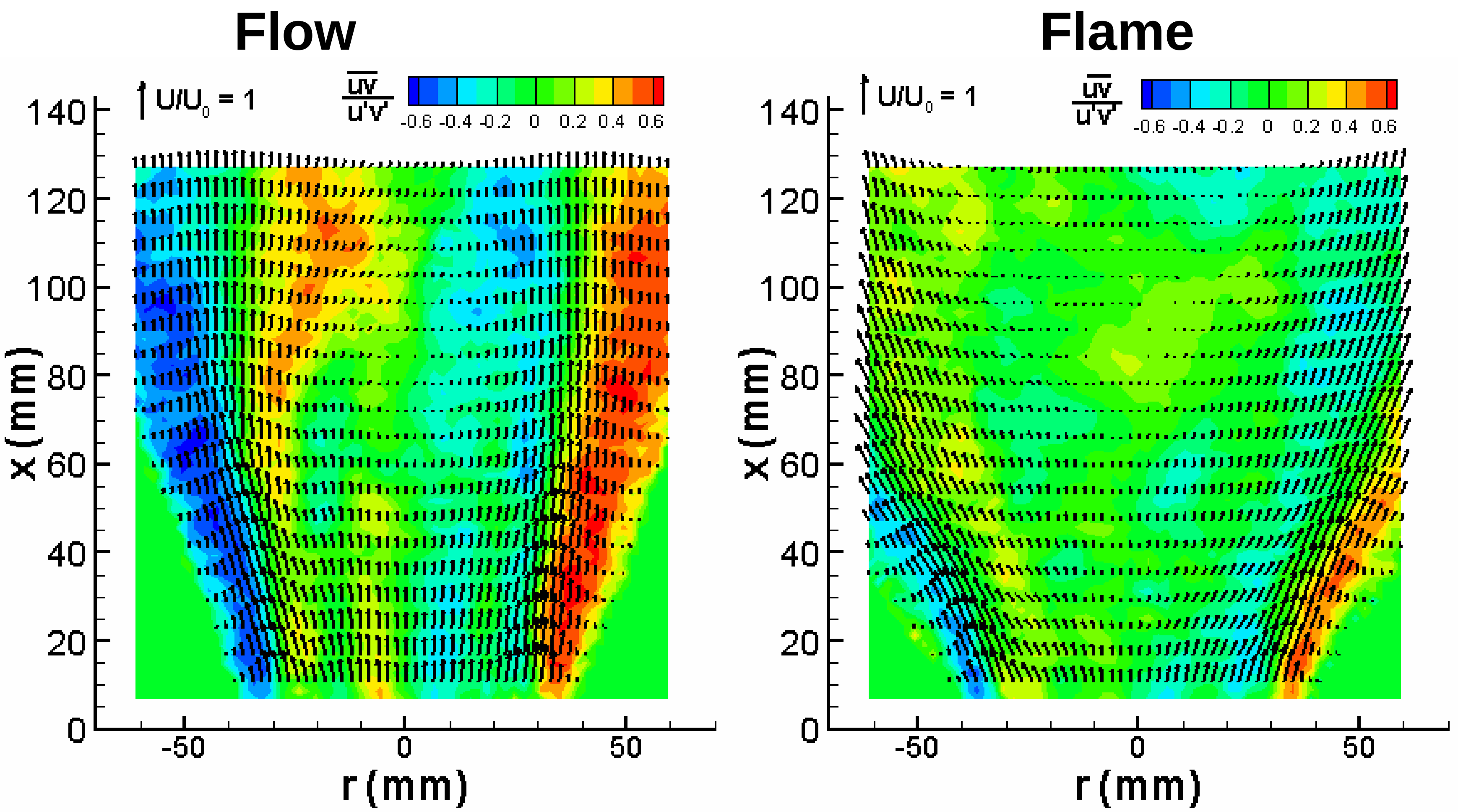
# Normalized mean vectors and Reynolds stress at $U_0$ = 15 m/s



# Normalized mean vectors and Reynolds stress at $U_0$ = 19 m/s

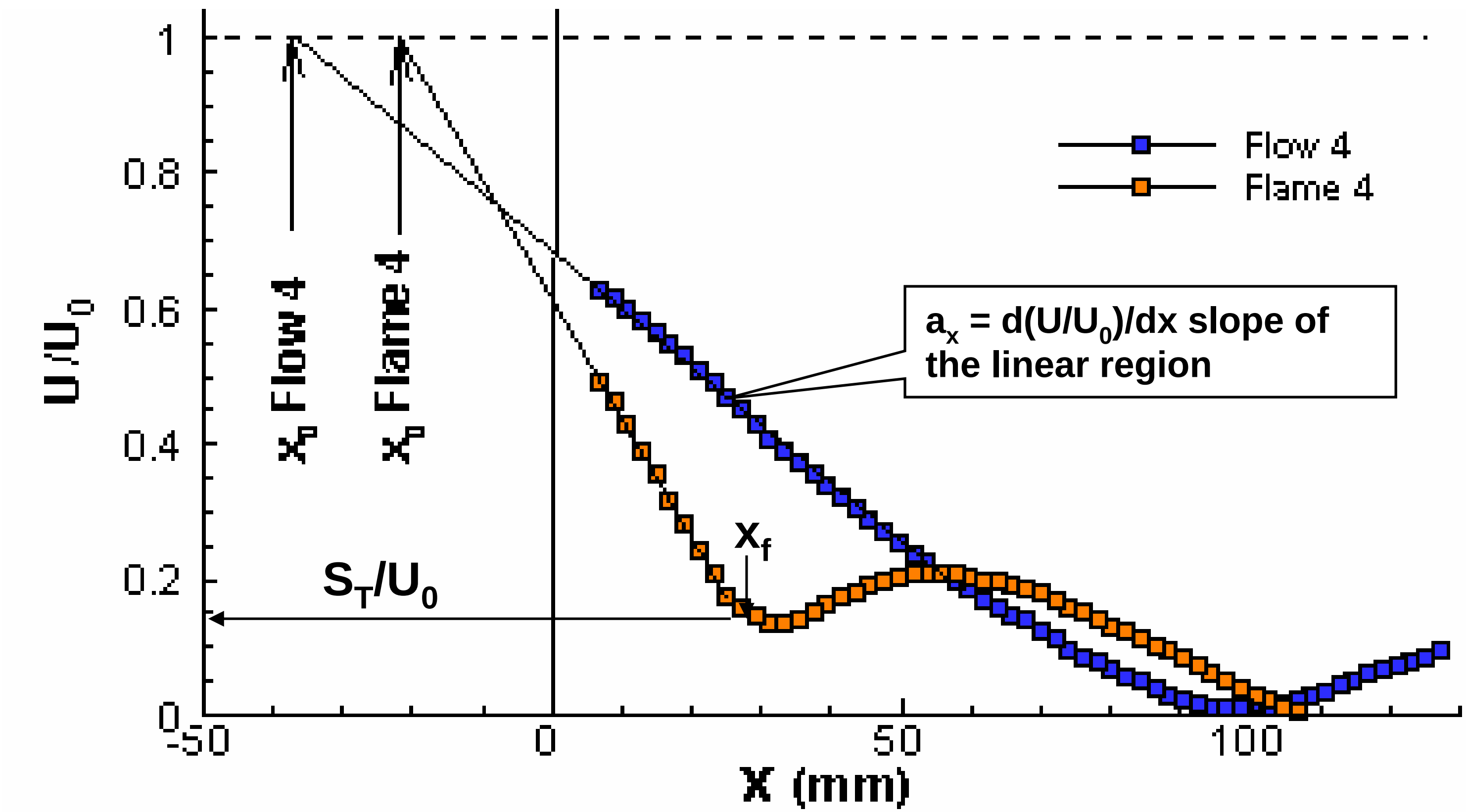


# Normalized mean vectors and Reynolds stress at $U_0$ = 22 m/s

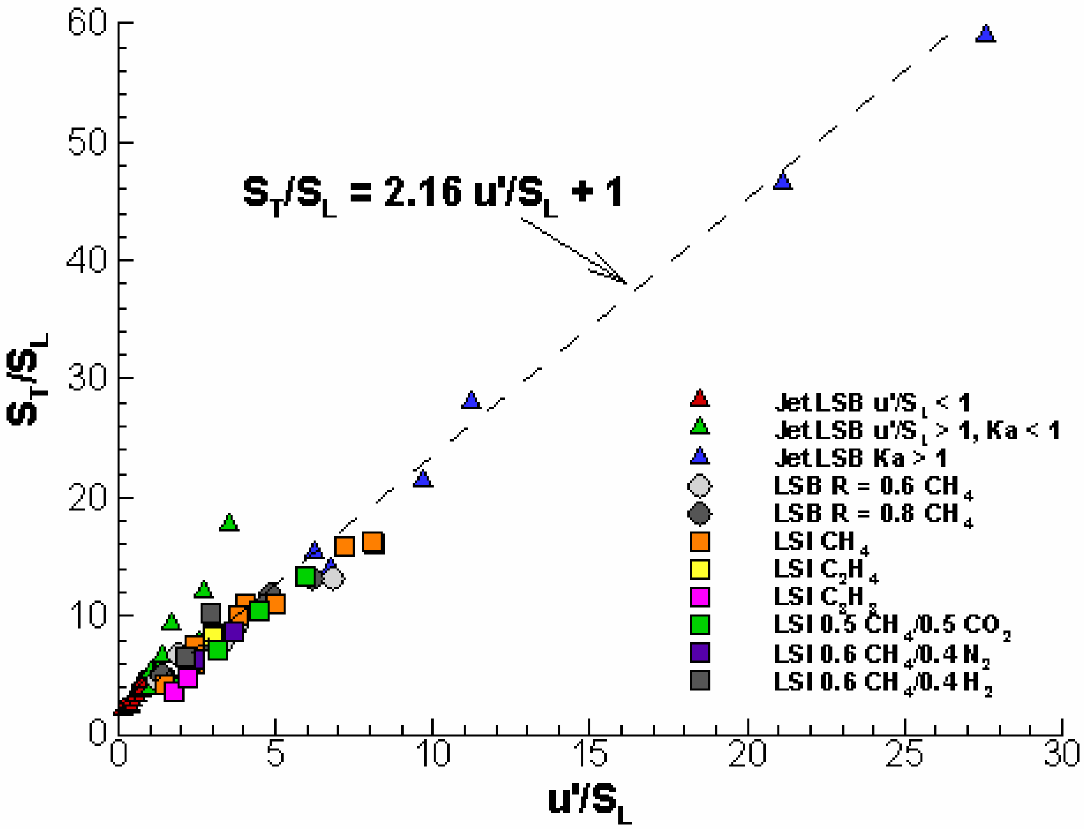


# PIV Measures the Parameters that Describe Flame/Flow Coupling in LSI

- **Four parameters deduced from the centerline velocity profile Virtual Origin, $x_0$, Normalized Axial Divergence Rate, $a_x$, Flame Position, $x_f$ and Turbulent Flame Speed, $S_T$**

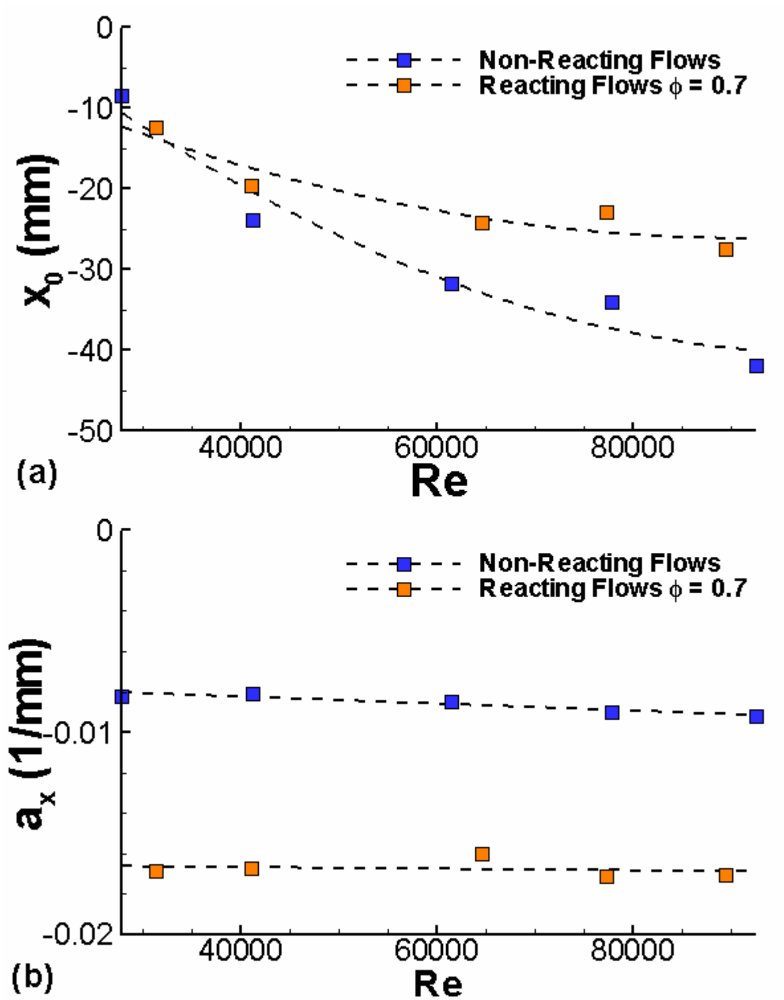


# $S_T$ of $CH_4$, $C_3H_8$, $C_2H_4$ and Diluted HC Flames Show Linear Correlation



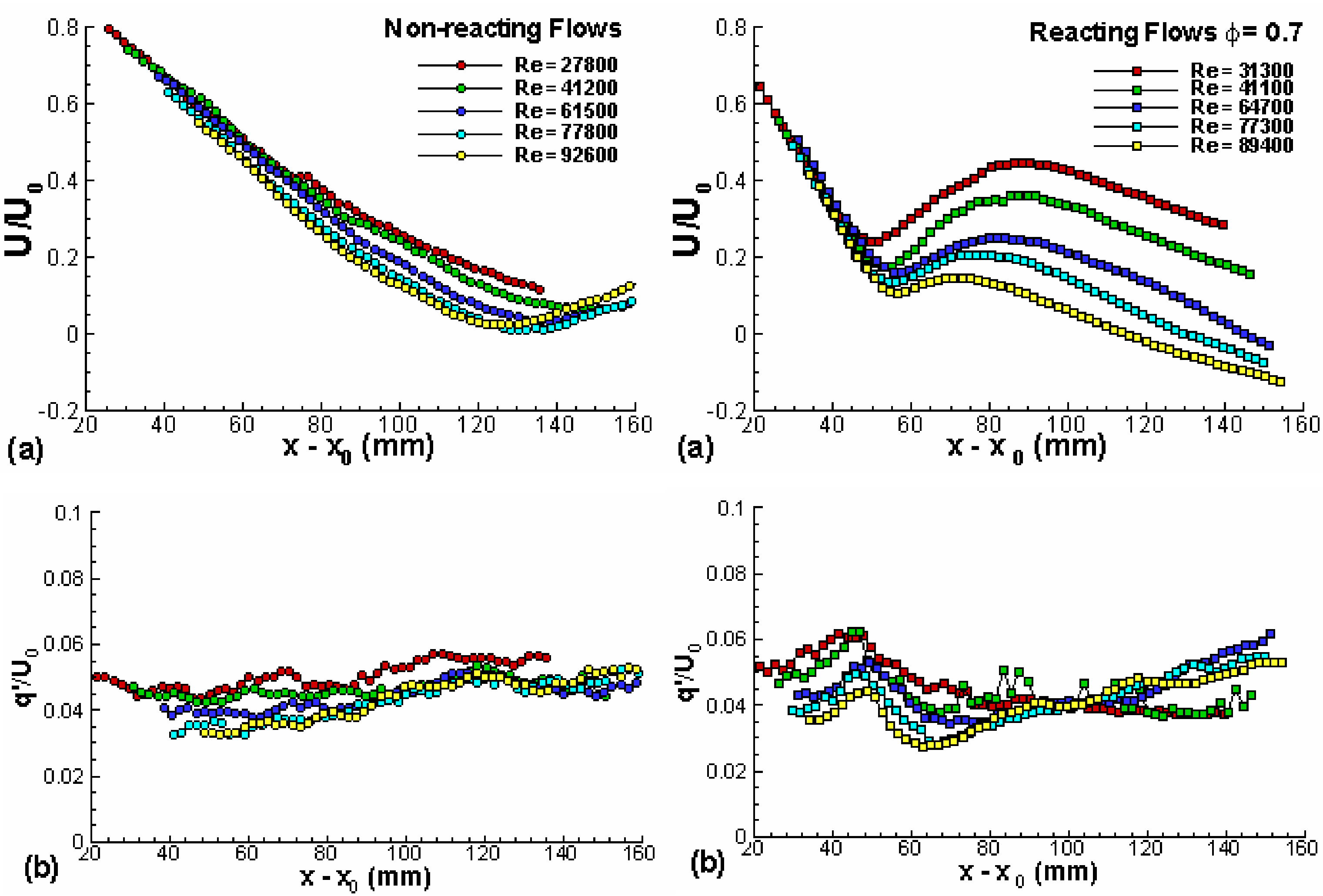

- $S_T$ from LSI flames consistent with those of previous studies
- Linear behavior unique to low-swirl combustion
- Additional data being obtained at higher $U_0$

# Trends of $x_0$, and $a_x$ with Reynolds Number Indicate Similarity




- **Virtual origin $x_0$ leveling-off at high Re**
  - **Slight shift of the divergence flow structures into the injector barrel with increasing velocity**
- **Normalized divergence stretch $a_x$ insensitive to Re**
  - **Combustion generates a systematic increase in $a_x$**
- **Nearfield flow structures have a similar form that is independent of power output**

# Similarity in the Nearfield Shown by Normalized Centerline Profiles



# Significant Implication of Similarity

- Provides an analytical means to quantify the flame/flow relationship by the use of $a_x$, $U_0$, $S_T$ and $x_f$
  - the axial velocity at $x_f$ is

$$U_o - \frac{dU}{dx}(x_f - x_o) = S_T$$

  - Divide through by $U_0$ and invoke $S_T$ correlation gives

$$1 - \frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_T}{U_0} = \frac{S_L}{U_0} + \frac{2.16u'}{U_o}$$

**invariant due to similarity (i.e. $a_x$)**

**asymptote at large $U_0$**

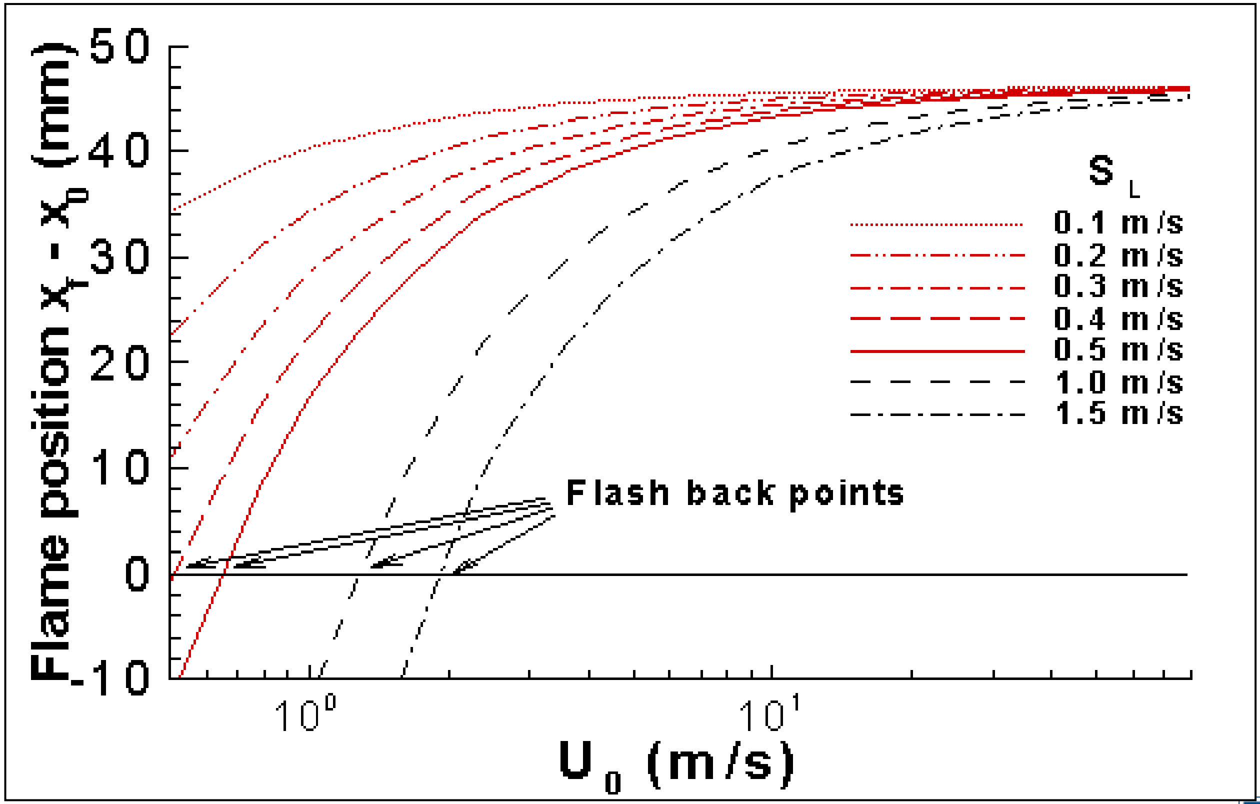
**small at large $U_0$**

**constant for plate turbulence**

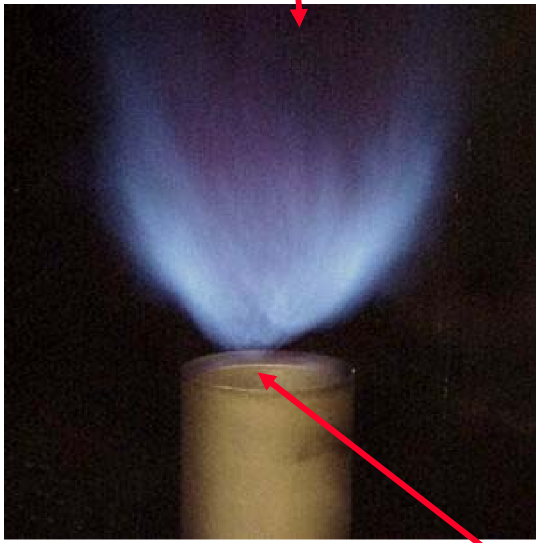
Flowfield similarity and linear $S_T$ correlations explains why flame remains stationary through a wide range of velocities and $\phi$

# Flashback and Flame Positions Predictable from Analytical Equation

- **Results imply that fuel effects are significant only at low $U_0$**
  - **Velocity at flash back correlates with $S_L$**
  - **Flame position independent of $S_L$ at large $U_0$**



# Flashback Considerations for Low-Swirl and High-swirl

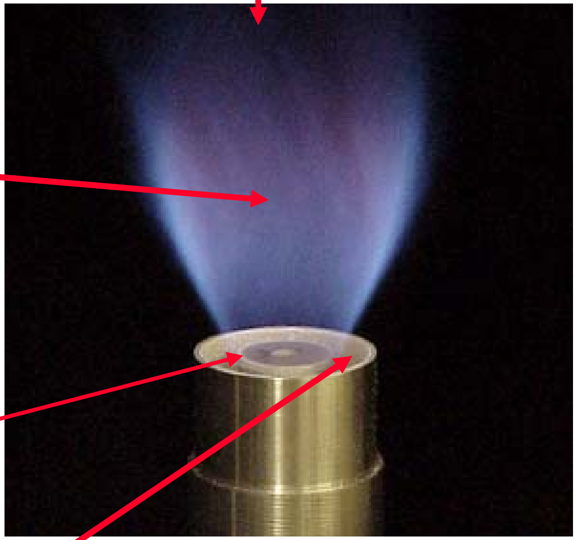


**Combustion oscillation flashback**

**Vortex breakdown flashback due to axial vorticity in recirculation region**

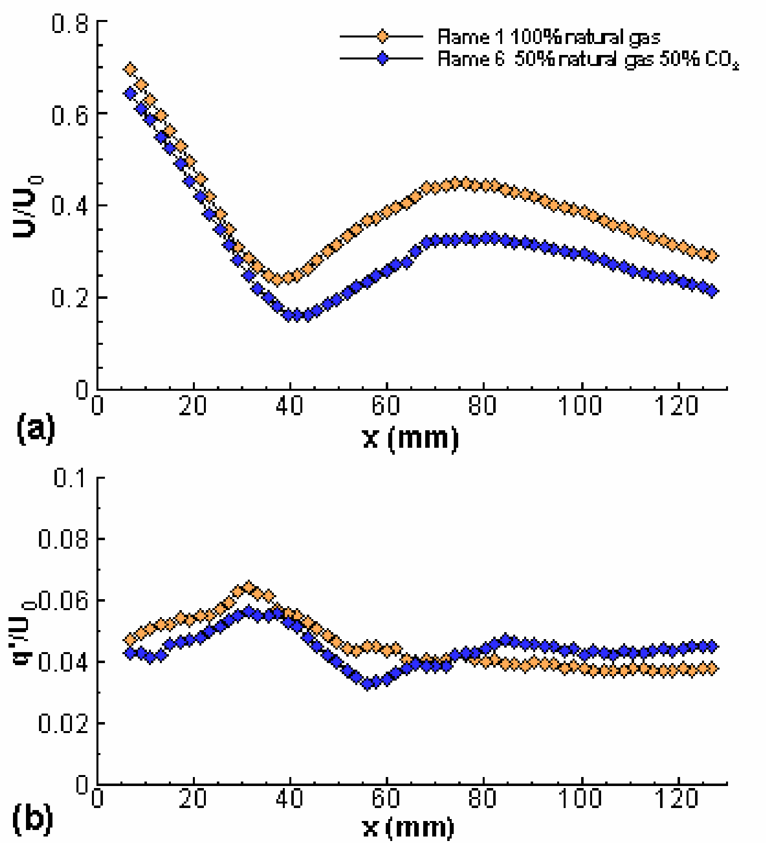
**Flashback through hot boundary layer at flame attachment region**

**Convective flashback – local velocity < $S_T$**

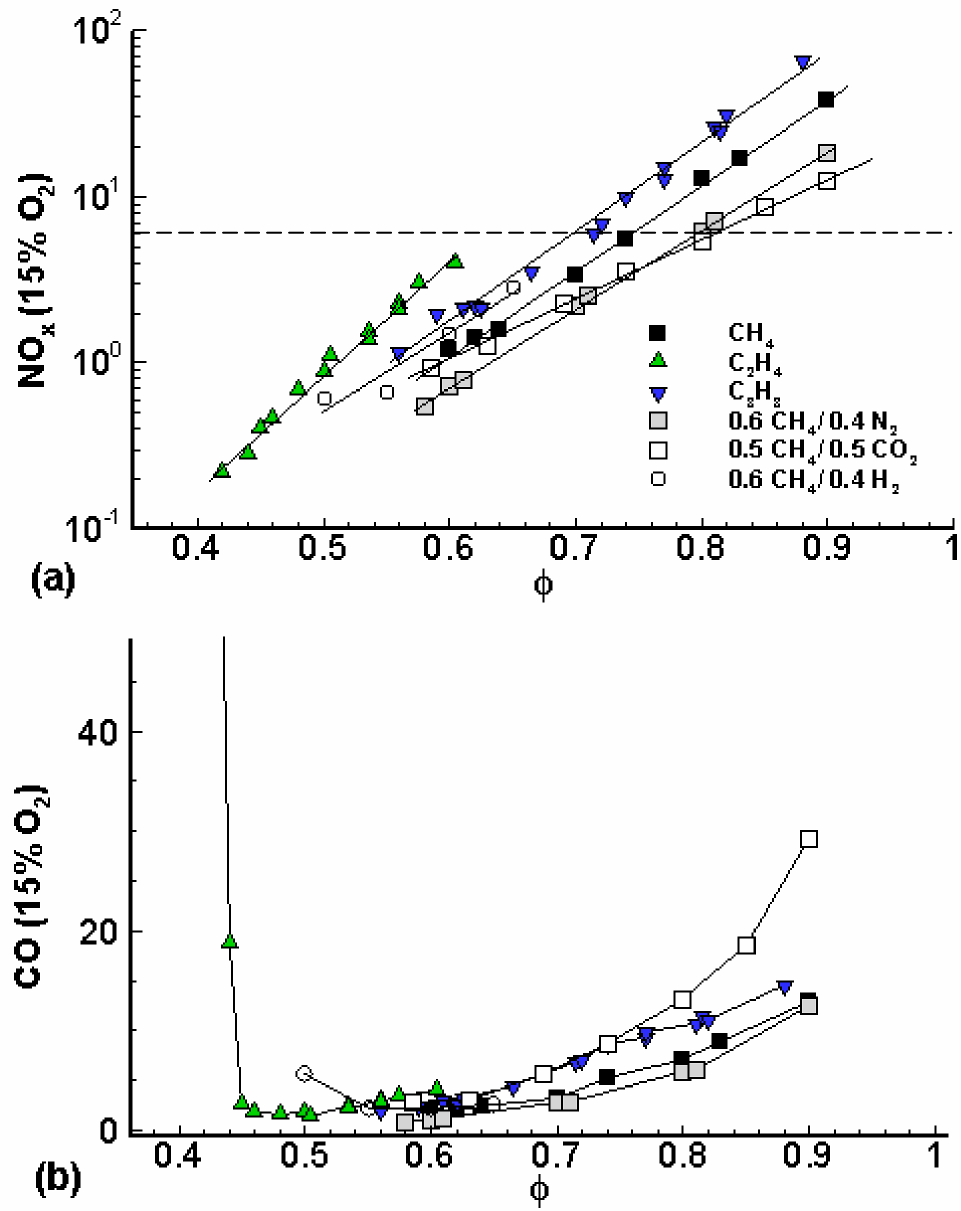


- **LSC analytical model addresses convective flashback**
- **Need studies on LSC vulnerability to combustion oscillation flashback**

# Flowfield Features Unaffected by Fuel Type




- Flowfield features of $CH_4$ and diluted $CH_4$ flames are the same
- Flame stabilization mechanism not affected by variation in fuel composition
- Slight shift in flame position due to slower burning flame

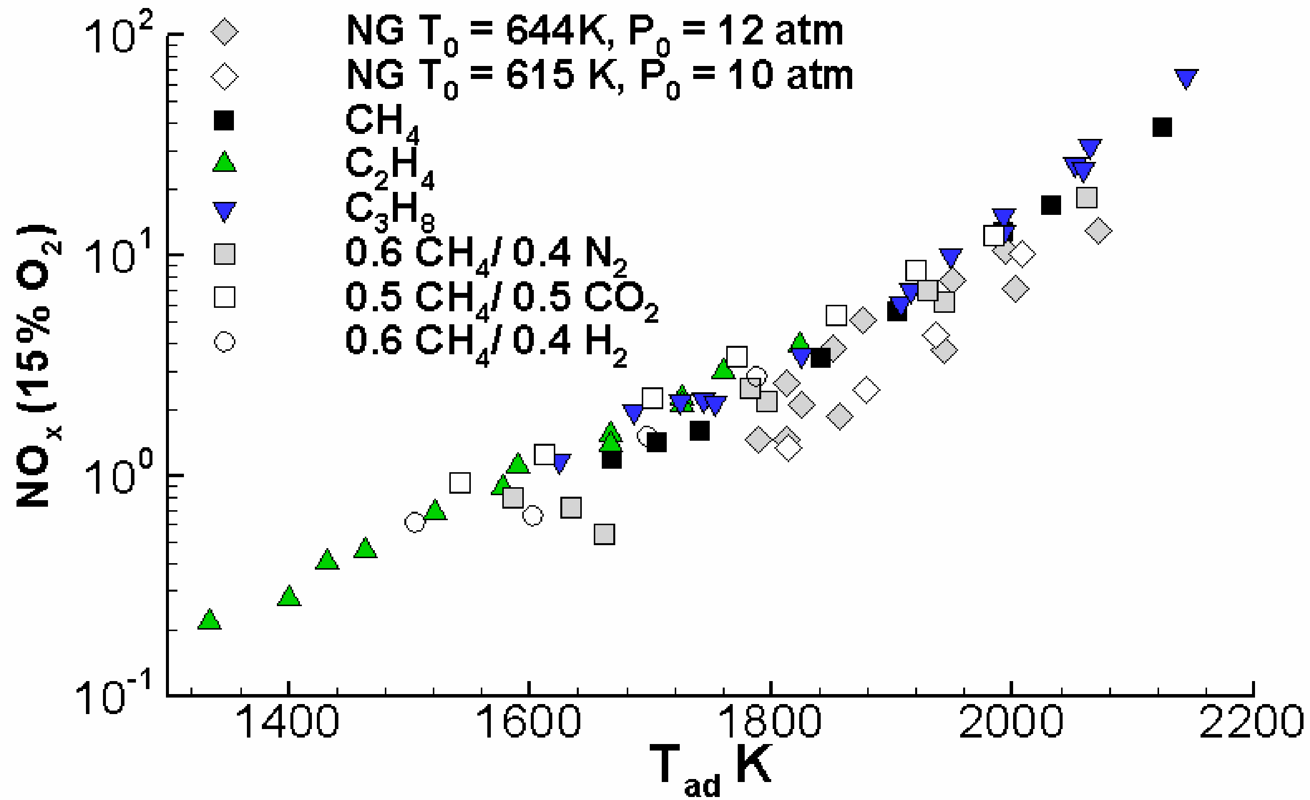



# LSI Supports Stable < 5 ppm $NO_x$ Hydrocarbon Flames

- Exponential $NO_x$ dependence on $\phi$
- CO emissions within acceptable limits

# $NO_x$ Emissions Show Log-linear Dependency on Flame Temperature

- $NO_x$ emissions from STP laboratory experiments consistent with data at gas turbine conditions
- Absence of strong recirculation in LSI may explain the correspondence between laboratory and GT emissions



# Preliminary Conclusions on Hydrocarbon Fuel-Flexibility Studies

- **LSI accepts all test fuels including $CH_4$ diluted with $H_2$**
- **LSI supports stable < 5 ppm $NO_x$ flames**
- **$NO_x$ emissions scale with adiabatic flame temperature**
  - $NO_x$ emissions from laboratory flames STP consistent with high pressure rig test data at turbine conditions
- **Significant adjustment may not be necessary for current LSI to fire with hydrocarbon fuel blends**
  - **$S_T$ of hydrocarbon and $CH_4$ flames have same correlation**
- **Recent high T, P rig-tests at Solar Turbines demonstrate firing with fuels from 550 Btu/ft$^3$ to 1250 Btu/ft$^3$**

# Considerations for Adaptation of LSI to Fuel-Flexible & IGCC Turbines

- **Changes in flame speed correlation will be the 1st order effect**
  - **Turbulent flame speeds for HC fuels have similar correlation as natural gas**
    - **Significant redesigning of swirler may not be necessary**
  - **Turbulent flame speed data for $H_2$ mixtures are lacking**
    - **Large uncertainties in laminar flame speed data for lean $H_2$ mixtures**
- **Changes in heat release will be the 2nd order effect**
  - **Changes in LSI flowfield correlates with combustion heat release**
- **LSI swirl rate can be adjusted to accommodate the fuel effects**
  - **Increase or decrease the swirl rate to optimize flame position**

# Part 4

# Scale-up Issues and Challenges for IGCC

# Issues and Challenges for Adapting LSI to Large Utility Turbines

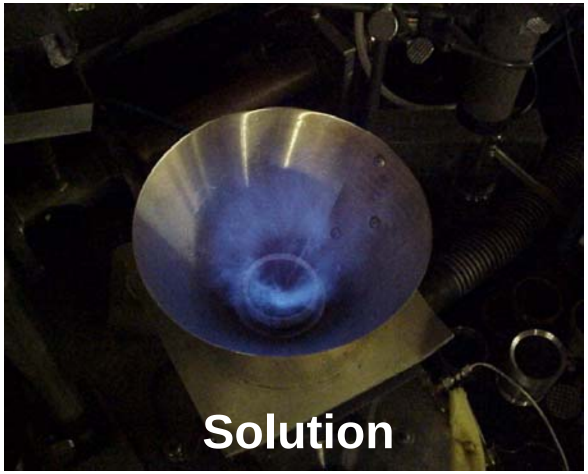
- **Natural gas engines**
  - Larger sizes – increase diameter of injector
  - Larger capacity - increase of 2 to 5 times over that of LSI for Taurus 70
  - Higher operating temperatures and pressures
- **Fuel-flexible and syn-gas engines**
  - Combustion properties of syn-gas flames similar to those of low-Btu hydrocarbon fuels
  - Scaling issues + fuel injector design and premixing
- **$H_2$ engines**
  - Distinct characteristics of $H_2$ flame due to high diffusivity and reactivity
    - Premixed turbulent $H_2$ flames not well understood
    - Demonstration of the feasibility of LSC for $H_2$ flames
  - Short auto-ignition time compare to hydrocarbons
    - Engineering design for fuel injection and mixing

# Laboratory Experiments on Premixed $H_2$ Flames in LSI

Lean premixed $H_2$/air flame at $\phi = 0.35$ & $U_0 = 20$ m/s captured by an IR camera

- Obtained the basic knowledge to evaluate the feasibility of LSC concept for $H_2$
  - Measured turbulent flame speed for $H_2$ flames and their coupling with LSI flowfield
- Studied flames burning with pure $H_2$ and $H_2$ diluted with 25% and 50% $N_2$ dilution (by volume)
  - Conditions with $T_{ad}$= 1200, 1320, 1380 K
- Varied swirl number from 0.57 < S < 0.41
  - Varied the blockage ratio and geometric pattern of the center plate
  - Much more convenient than changing swirl vane angle
- Measured lean blow-out and flowfield characteristics at $9 < U_0 < 20$ m/s
  - Define optimum LSI configuration for $H_2$
  - PIV data analyzed to obtained $S_T$ correlation and other flowfield parameters

# Open $H_2$ Flames Attach to Burner Rim at High $\phi$

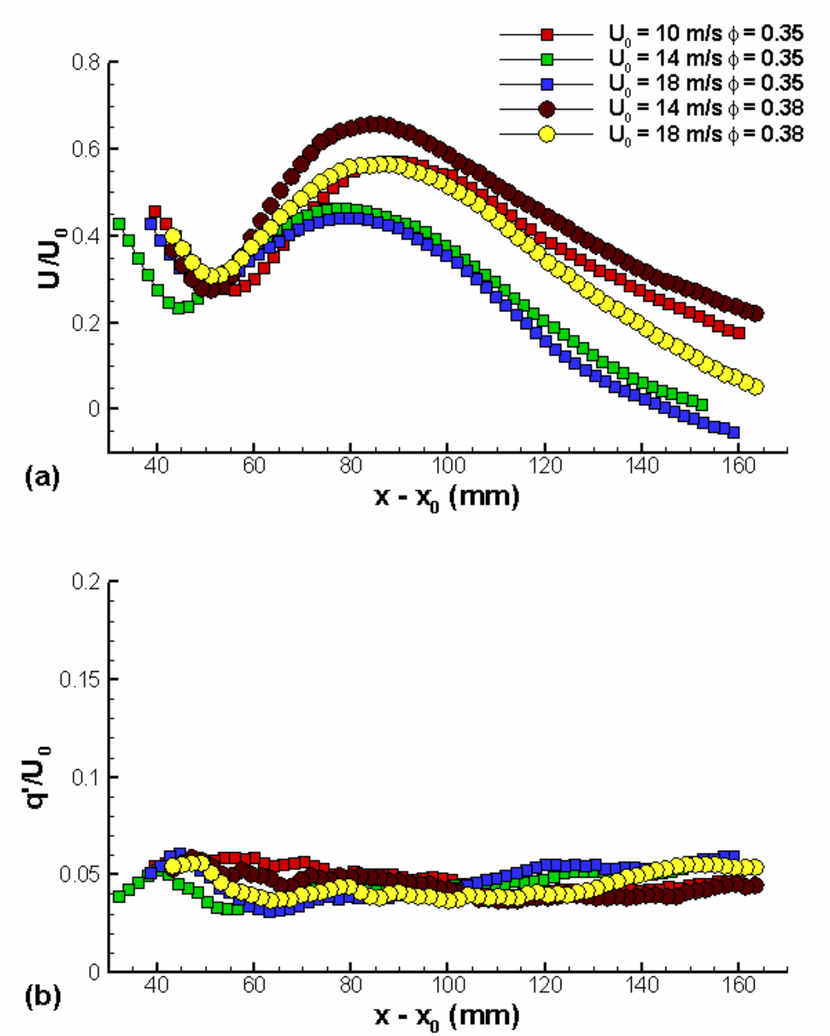




- Highly diffusive $H_2$ burning in low-velocity region in the shearing region between the premixture and room air
- Attachment represents an upper limit for the laboratory studies
  - Changes in the outer flowfield characteristics affect the core flow
- For turbine application, flame attachment can be mitigated by an angled expansion at the nozzle exit

# Relaxing Swirl Number to Optimize for $H_2$ Flames

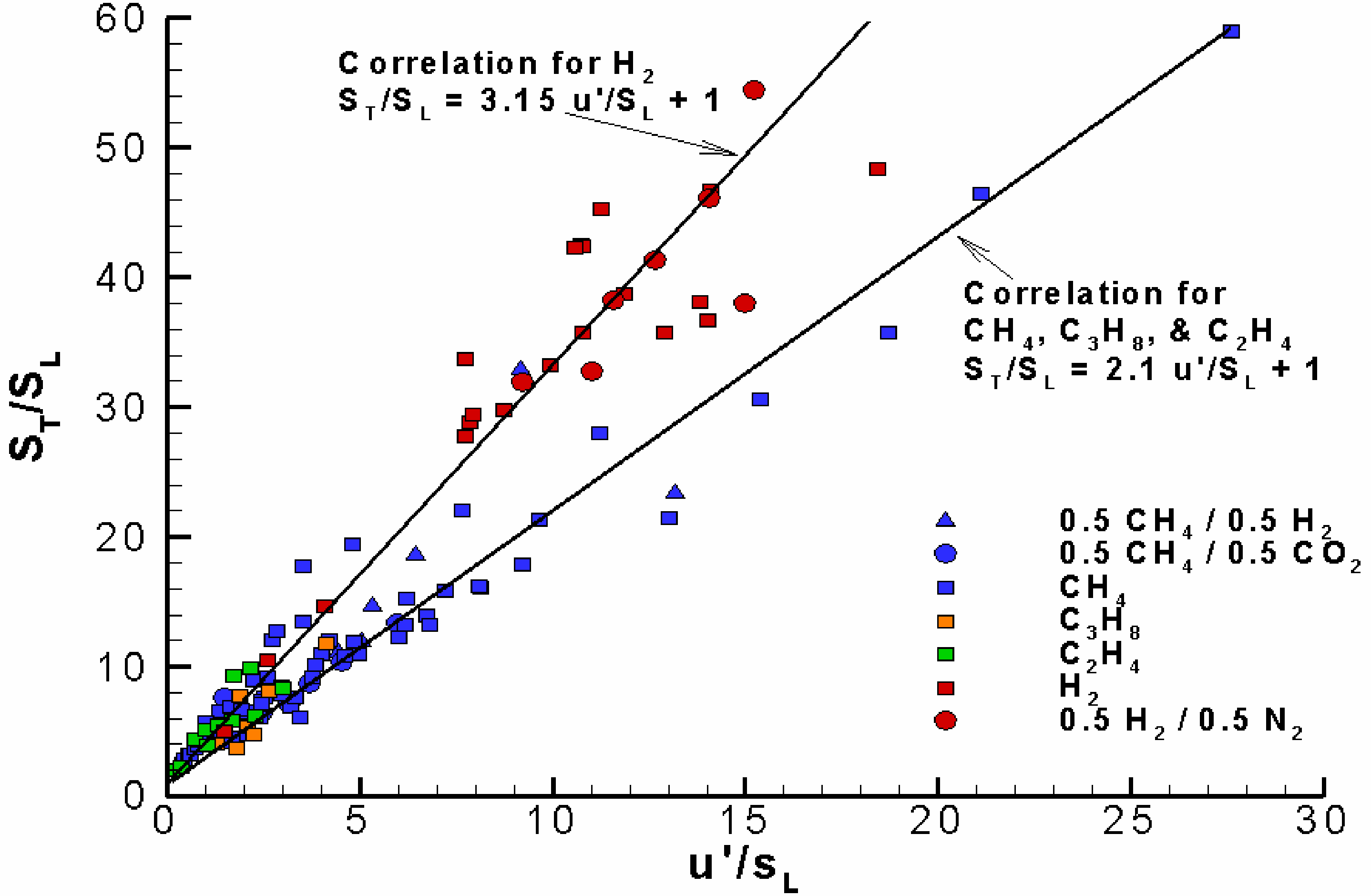
- **Current LSI (S = 0.54) stabilizes $H_2$ flames that are very close to the nozzle exit**
  - **Flame attachment occurs for $\phi > 0.3$**
- **Lowering S from 0.54 to 0.43 generates more lifted flames and pushes flame attachment to $\phi > 0.4$**
  - **Flame position trend consistent with prediction of the analytical model**
- **LSI with S = 0.51 offers best performance for laboratory studies**
  - **LSI for $H_2$ is not significantly different than LSI for hydrocarbons**

# Flowfield Features of $H_2$ Flames Are Same as HC Flames




- Centerline velocity profiles show similarity features in the nearfield
- Flowfield features in the farfield are no different than those of HC flames
- Similarity is also shown by radial profiles

# $S_T$ of $H_2$ Flames Have Linear Correlation With a Higher Coefficient Than HC Flames



# Laboratory Studies Show LSI Amenable to Burning Pure $H_2$

- Dominant flame/flow coupling processes of $H_2$ and hydrocarbon flames are the same
  - Effects due to high diffusivity are impediments to open flame laboratory studies and can be addressed by engineering means
- Higher $H_2$ flame speed correlation accommodated by a small reduction of the swirl number
- Demonstrate the viability of the analytical model for $H_2$ LSI design
- Encouraging results useful for guiding the sub-scale $H_2$ LSI prototype for demonstration at high T&P

# Part 5

# R&D Needs for $H_2$ Turbines

# Many Issues and Uncertainties for Development of LSI for $H_2$ Turbines

- **Fundamental Issues**
  - Ignition delay
  - Turbulent flame speed correlation
  - Unknown properties of $H_2$ flames at high pressures
    - Reaction rate
    - Flame volume
  - Predict emissions at relevant conditions
  - Instability characteristics of LSI
  - Modeling & simulation
  - Flowfield/emission coupling

- **Engineering issues**
  - Scaling to larger sizes
  - Fuel injection, premixer & nozzle design
  - Verify operation at higher T & P
  - Optimize for fuel/flame properties
    - Syn-gas versus $H_2$
  - LSI/Combustor layout
  - Integrate with other components
  - Operations & Controls
    - $H_2$ flames are invisible

# Developmental Steps Toward LSI for $H_2$ Turbines

- **Applied knowledge gain from laboratory studies to optimize prototypes for $H_2$ (Part 4 of this talk)**
- **Pressurized sub-scale testing at research facilities to explore overall behavior**
  - **Georgia Tech. – mapping the operating regime using a small 2.54 cm diameter prototype**
  - **NETL – detailed investigation of scalar and velocity fields with a 5 cm diameter prototype**
- **Seek guidance from technical advisors on fuel compositions, firing temperatures and test conditions**
- **Coordinate and merge knowledge from University and Nat'l Lab researchers**
- **Share results with OEMs and vendors**
  - **Evaluate feasibility for each system**
- **Plan next developmental phase**

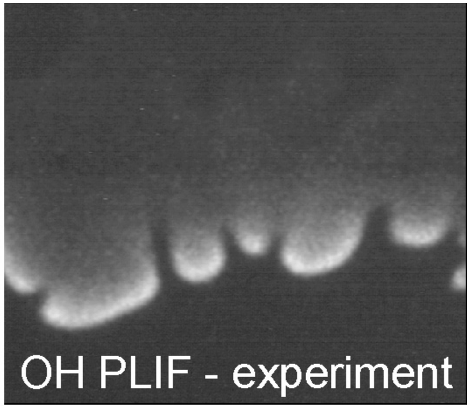
# Ignition Delay, $\tau$

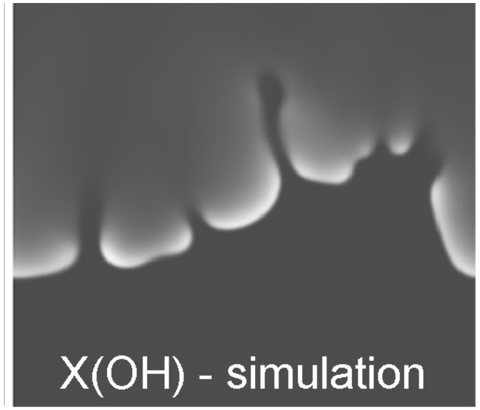
- Residence time of $H_2$ reactants within the combustor cannot be longer than the auto-ignition delay time
  - Prevent premature ignition
- $H_2$ ignition delay data not yet available at relevant gas turbine temperatures and pressures
  - Measurements are being made at Univ. of California, Irvine (flow channel) and at University of Central Florida (shock tube)
- Data are encouraging for utilization of lean premixed $H_2$ combustion for IGCC

# $H_2$ Turbulent Flame Speed Correlation at Relevant Gas Turbine Conditions

- Need in-situ $H_2$ flame speed data for LSC development
  - Turbulent flame speeds are strongly dependent on system configuration
  - Data measured in transient flames inside constant volume combustion vessels have non-linear characteristics that contradict the LSC results
- Significant experimental challenges for laser anemometry measurements in high-pressure flow channels
  - Transmitting laser and scattered signal through windows reduces signal to noise
  - Operational difficulties associated with cleanup of fine particles deposited on windows
- University and National Lab researchers rising to this challenge
  - Overall trend can be inferred by observing LSI $H_2$ flames at high T and P
  - Detailed measurements at selected data points for quantitative comparison with results from STP laboratory experiments

# Premixed $H_2$ Flame Properties Not Well-Characterized at Relevant Conditions




- **Reaction zone structures of turbulent $H_2$ flames are different than those of hydrocarbon flames**
  - **$H_2$ flames are inherently unstable due to preferential diffusion**
  - **Laboratory experiments and simulations of turbulent $H_2$ flame show non-uniform heat release and local extinction**
    - **$H_2$ flames may need large combustion chamber**
- **Heat release model for hydrocarbon flames are not suitable for $H_2$ flames**
- **Research needs**
  - **Improved chemical kinetics and transport for lean $H_2$ mixtures**
  - **Effects of intense turbulence and elevated temperatures and pressures on preferential diffusion effects**

# Predicting LSI $NO_x$ Emissions at Relevant Conditions

- **LSI $NO_x$ emissions correlate with flame temperature over a large range of inlet T & P**
  - Nitrogen chemistry has temperature and pressure dependencies
  - Need improved understanding of prompt $NO_x$ versus thermal $NO_x$ formation in ultra-lean flames
- **Laboratory experiments show impact of recirculation on $NO_x$ formation**
  - LSI generates high $NO_x$ when placed in a large enclosure that promotes internally recirculating flow
  - Characterizing the residence time of the hot products within the combustor may be the key to explain the differences in $NO_x$ emissions of low-swirl and high-swirl combustion
- **Basic studies of the flowfield/emissions coupling will be beneficial to LSI development**

# Combustion Dynamics of LSI

- **LSI in T70 engine shows different acoustic signature**
  - **Acceptable pressure fluctuations at frequencies different than SoLoNOx high-swirl injectors**
- **Pressure/heat release coupling of LSI has not been characterized**
  - **Propagating nature of LSI flames and absence of well developed flow recirculation affect how the flame responds to external excitations**
- **University and Nat'l Lab researchers are developing research plans to study LSI oscillation characteristics**
  - **Side-by-side comparison of low-swirl and high-swirl combustion oscillation will give fresh insights to understand combustion dynamics**

# Summary

- LSC is a cost-effective and robust enabling ultra-low emissions technology for natural gas turbines and shows very good promise for fuel-flexible turbines utilizing blended hydrocarbon fuels
- Principle of LSC is described by top level model that can be used to guide its scale-up for large utility turbines
- LSC shows good promise for large turbines operating on natural gas and other hydrocarbons
- Development for syngas and $H_2$ turbines requires empirical inputs as well as insights on fundamental combustion properties of $H_2$ flames to guide the adaptation

# Thank You for Your Attention

# We Want Your Feedback

- **If you are in the audience please send an e-mail to ronwolk@aol.com acknowledging your participation in this web-cast**
- **For questions and comment on the technology, please e-mail me RKCheng@lbl.gov**