Turbulent Flame Propagation Characteristics of High Hydrogen Content Fuels

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Presentation Outline

- Motivation
- Results From Previous UTSR Program
- Current UTSR Program Overview
- Status Updates
- Future Work

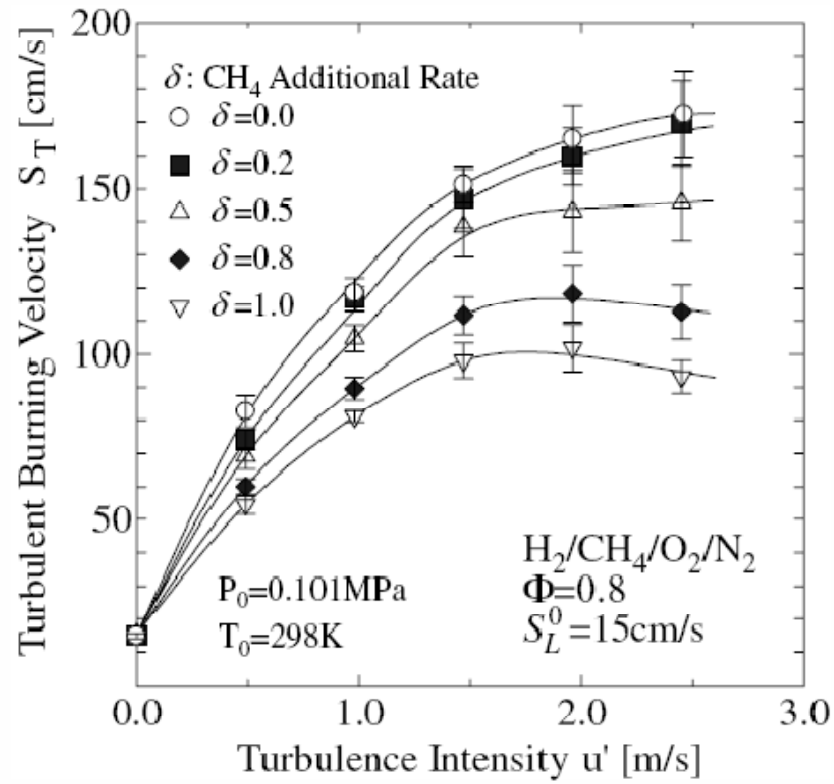
Motivation

- Turbulent flame speed, S_T, is a key combustion parameter that impacts the performance of combustion systems
  - Flame length
  - Emissions
  - Blowoff
  - Flashback
  - Combustion instabilities

- Little is known about S_T at GT realistic conditions, particularly fuel sensitivities

Motivation: Fuel Effects

- Data show that S_T varies with fuel, even at constant S_L and u'
  - Important issue for HHC fuels, due to variability in mixture constituents
  - Lipatnikov and Chomiak (2005), Driscoll (2008)
- Research needs:
  - Little data available for S_T at realistic conditions and for the HHC fuels of interest



Ref. Nakahara et. al. AIAA Journal, Vol. 46, No. 7, 2008

A.N. Lipatnikov, J. Chomiak, Progress in Energy and Combustion Science 31 (2005) 1–73
J.F. Driscoll, Progress in Energy and Combustion Science 34 (2008) 91–134

Flame Speed Definitions and Measurement Approach

- S_T is definition dependent
  - Recommended approaches (Int'l Workshop on Premixed Turbulent Flames):
    - $S_{T,GC}$ – Global consumption speed
      - Approach used in previous program
    - $S_{T,LC}$ – Local consumption speed
    - $S_{T,GD}$ – Global displacement speed
    - $S_{T,LD}$ – Local displacement speed
      - Measurement approach to be primarily utilized in this program

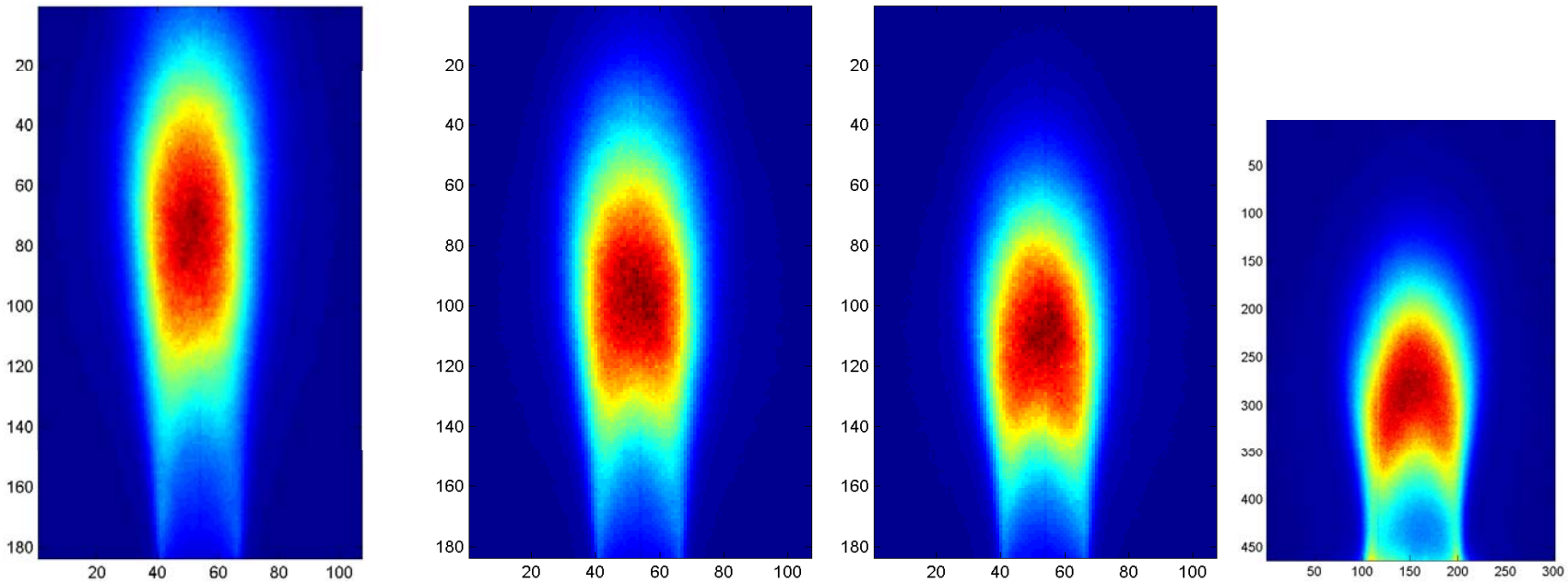
Cheng, R. K. and Gouldin, F. C. (2004) International Workshop on Premixed Turbulent Flames. http://eetd.lbl.gov/aet/combustion/workshop/workshop.html.

Results From Previous UTSR Program

- Demonstrated importance of fuel composition on global consumption speed at high turbulence intensity

- Data taken over a wide range of conditions demonstrating robustness of effect
  - Multiple burner diameters – length scale effects
  - High preheat temperatures
  - Various mean flow velocities
  - Range of fuel compositions and equivalence ratios
    - H_2/CO and CH_4
  - Large range of turbulence intensities – $u'/S_L >> 1$

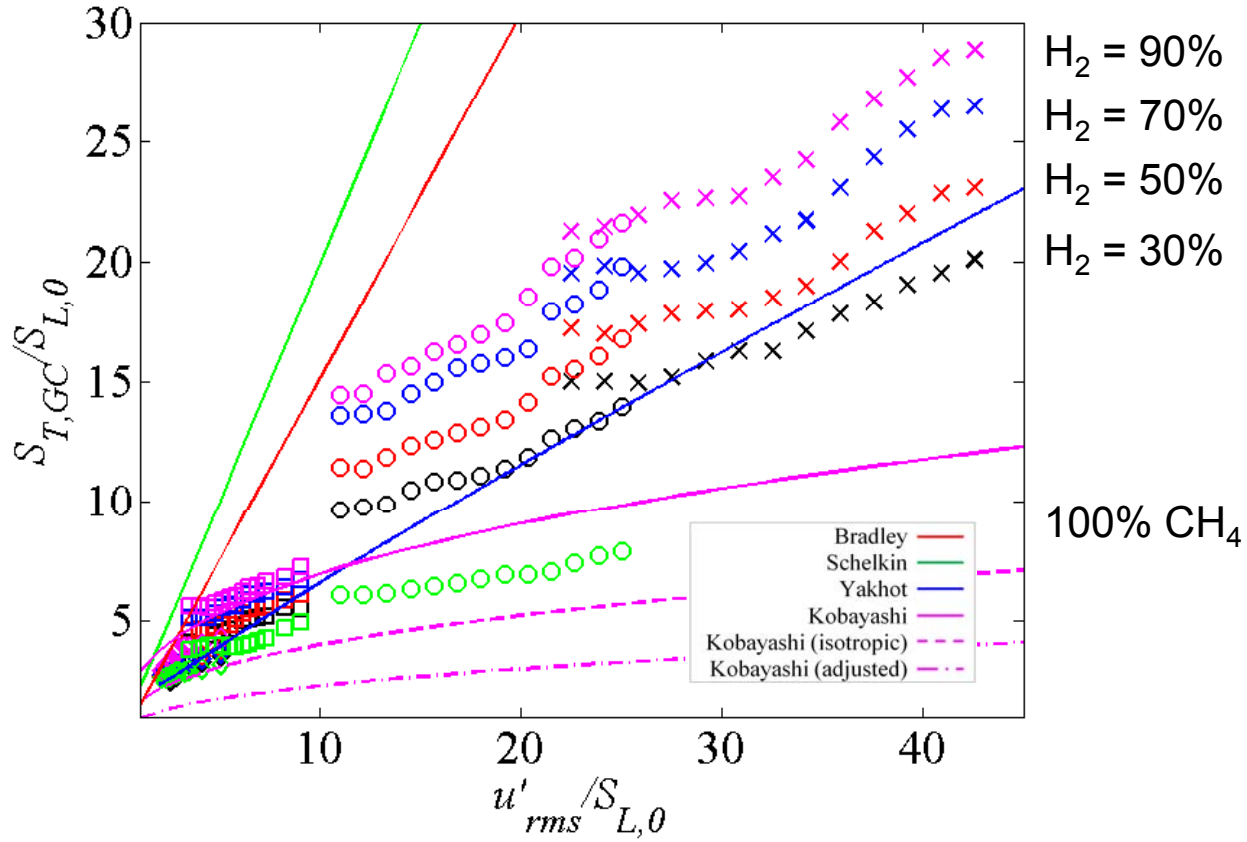
Average Flame Images – H_2 Content Effect (Fixed $S_{L,0}$ = 34 cm/s)



30% H_2 , Φ = 0.59 40% H_2 , Φ = 0.56 50% H_2 , Φ = 0.53 90% H_2 , Φ = 0.46

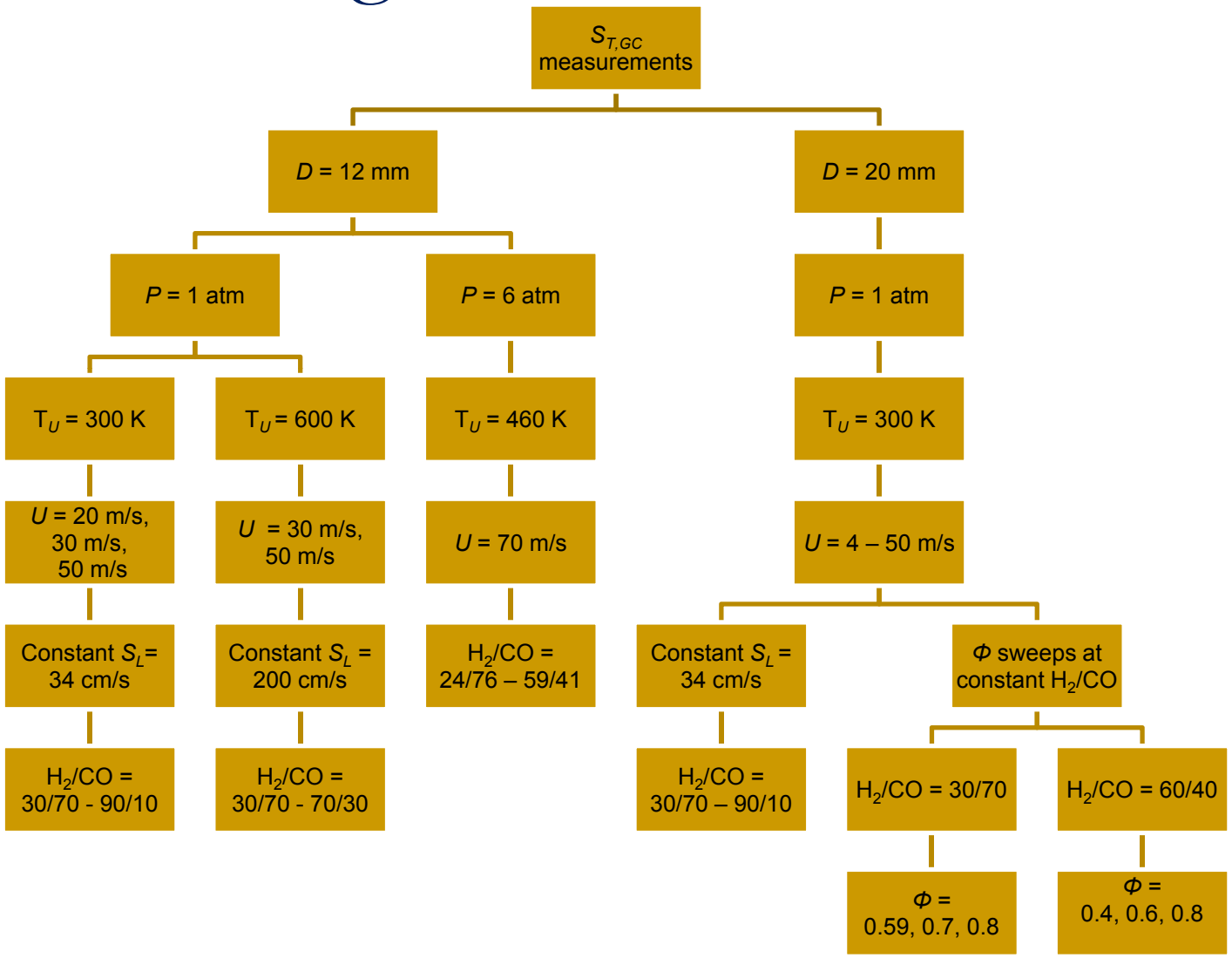
- Clear increase in S_T observed at constant $S_{L,0}$ as H_2 percentage increases
  - $u'/S_{L,0}$ >> 1 (= 45 in this data)
  - U = 50 m/s, TI = 19.2%

Varying H_2/CO Ratio



- D = 20 mm, U = 4 – 50 m/s, H_2 = 30% - 90%, $S_{L,0}$ = 34 cm/s, T = 300 K
- Data shows clear increase of $S_{T,GC}$ with H_2 content at fixed $S_{L,0}$

Previous Program Measurements



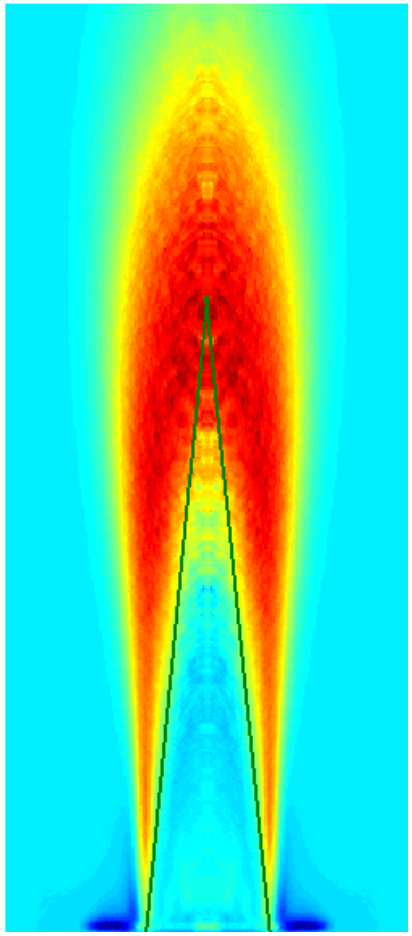
Current UTSR Program Overview

- Primary objectives:
  - Global and local turbulent flame speed measurements
  - Developing physics-based models
- Turbulent Flame Speed measurements
  - Extension of global consumption speed data
  - Local, instantaneous turbulent flame measurements
  - Stratified mixtures
- Physics-based modeling of turbulent flame characteristics

Global Consumption Speed

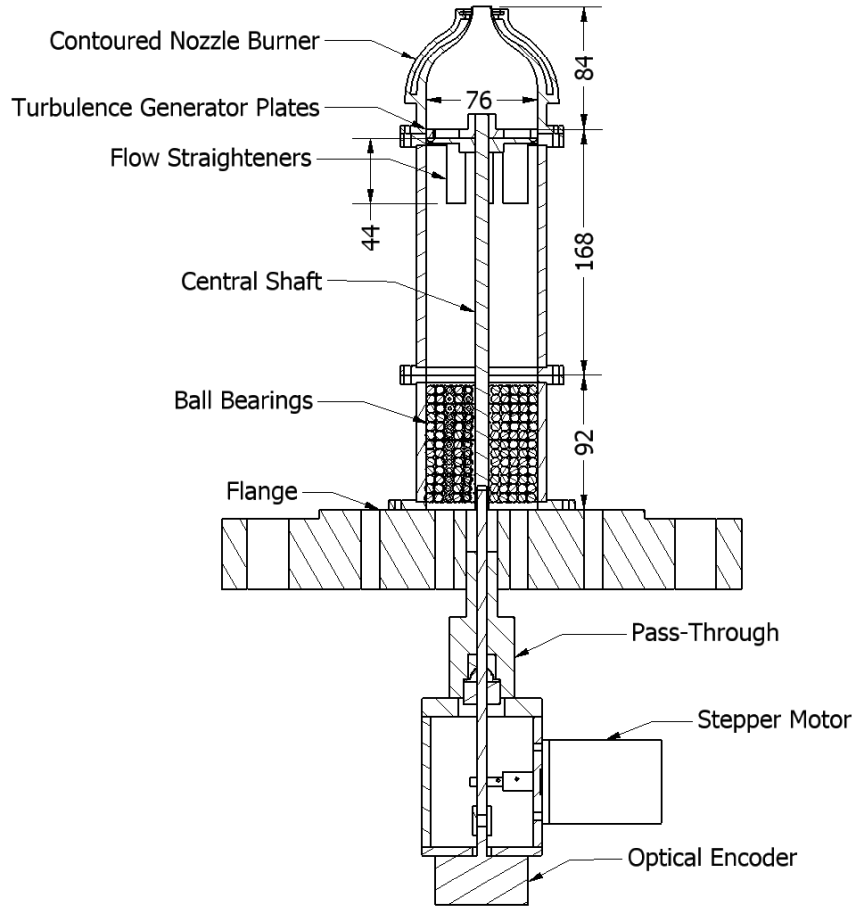
- Used for Bunsen flame configurations and other envelope flames
- Method used in previous UTSR program to quantify S_T for syngas and CH_4 flames
- Will be utilized in the current program to study the effects of diluents on HHC fuels

$$S_{T,GC} = \frac{\dot{m}_R}{\rho_R \overline{A}_{<c>}}$$



Extension of Global Consumption Speed Data

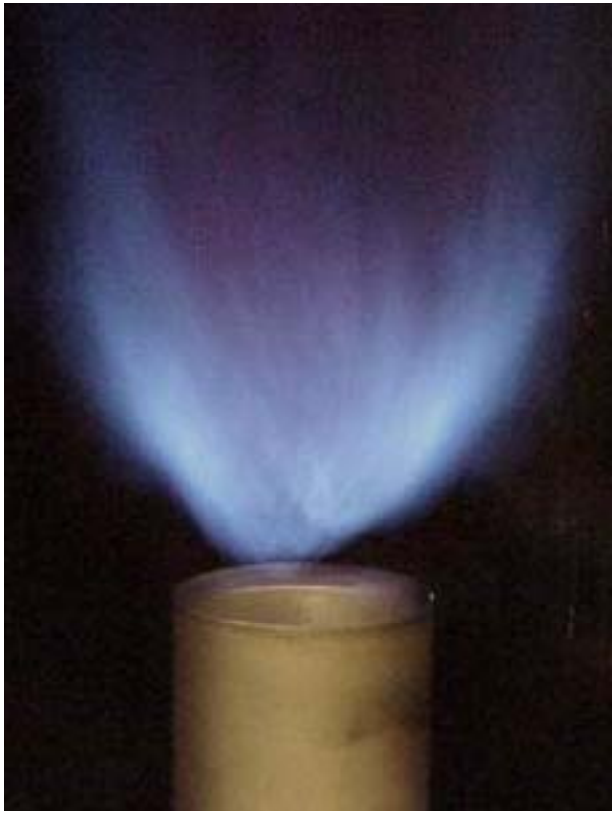
- Measurements to be taken with Bunsen burner configuration
  - Requires no facility modifications
- Fuel compositions: $H_2/CO/CH_4$
- Diluents: $N_2/H_2O/CO_2$
- Pressures up to 20 atm and preheat temperatures up to 800 K



Local Displacement Speed Measurements

- Will utilize low swirl burner (LSB) for measurements
- Measure axial velocity along centerline to determine S_T

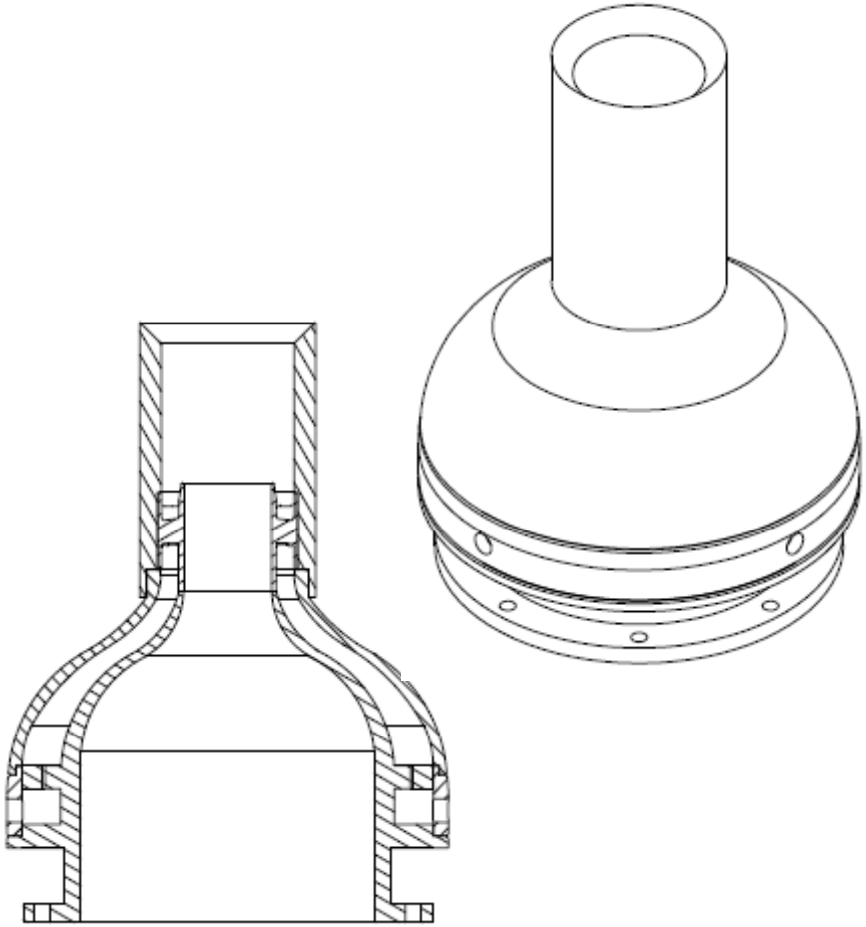
$$S_{T,LD} = \vec{U}_f - \vec{U}_r = |U| \sin\theta$$



Cheng, R. K., D. Littlejohn, et al. (2008). "Laboratory Studies of the Flow Field Characteristics of Low-Swirl Injectors for Adaptation to Fuel-Flexible Turbines." Journal of Engineering for Gas Turbines and Power **130(2): 021501.**

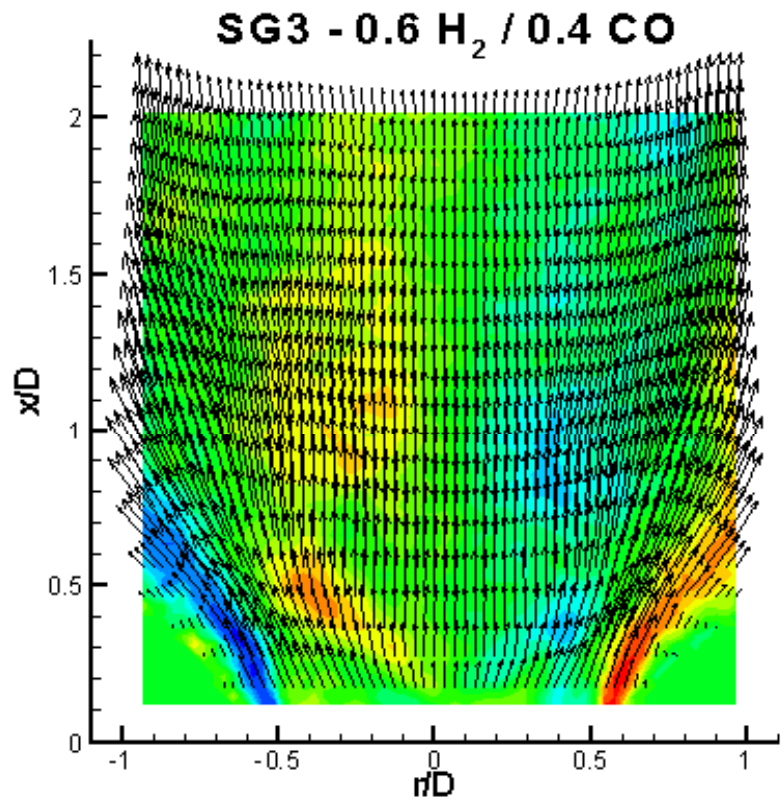
Burner Modifications

- Burner consists of two separate flow channels:
  - Central non-swirling region
  - Outer swirling region
- Each flow circuit will be separately controlled to allow for on-the-fly variations of the swirl number



LSB Flow Field Characteristics

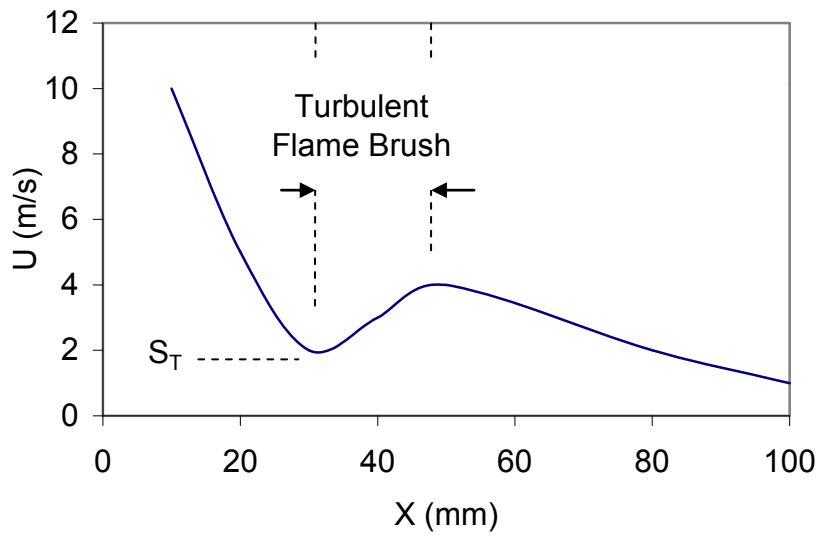
- Along centerline, flame is locally normal to approach flow
  - Quasi-1D geometry
- Swirl in outer region causes flow divergence in central region
  - Creates axially decaying axial velocity profile along centerline
- Flow field to be characterized with PIV



Littlejohn, D., R. K. Cheng, et al. (2010). "Laboratory Investigations of Low-Swirl Injectors Operating With Syngases." Journal of Engineering for Gas Turbines and Power **132(1): 011502-011508.**

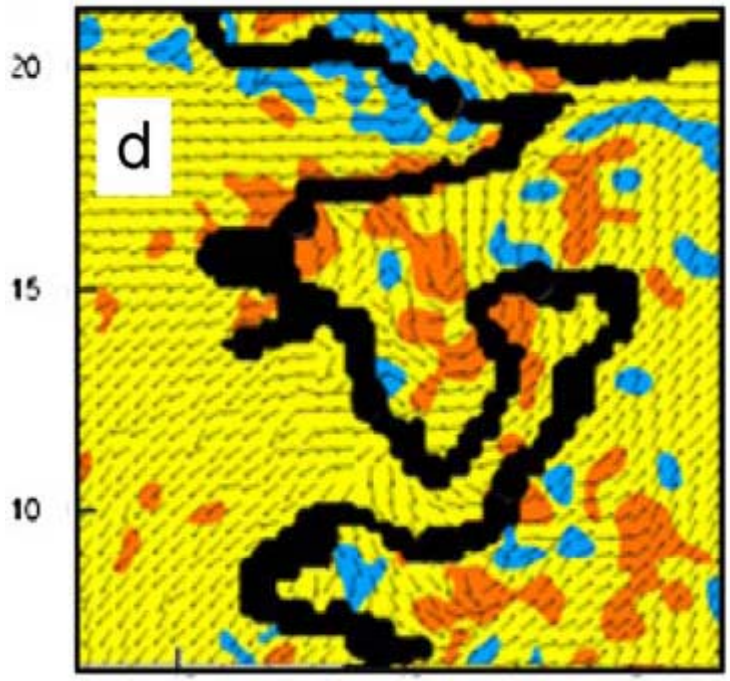
Local Flame Speed Measurements

- Local flame speeds can be found from PIV measurements
- Turbulent flame speed is found from local minimum in axial velocity
  - Corresponds to leading edge of the turbulent flame brush



Simultaneous Flow/Flame Measurements

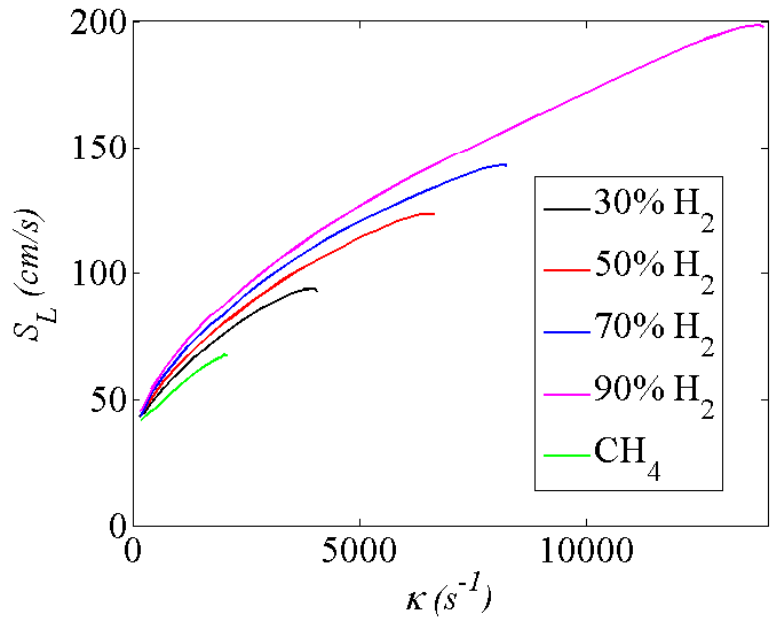
- Simultaneous high speed PIV/OH-PLIF will be performed to determine instantaneous, local flame behavior
- Allows for study of evolution of flame edge and interaction with turbulence
- Can determine local laminar flame speed, turbulence intensity, and stretch rate
- Useful for comparing with turbulent flame speed predictions and in turbulent combustion modeling



Driscoll, J. F. (2008). "Turbulent Premixed Combustion: Flamelet Structure and its Effect on Turbulent Burning Velocities." Progress in Energy and Combustion Science **34(1): 91-134.**

Strained Flame Calculations

- Strained flame calculations will be performed for all fuel blends investigated
- Relates laminar burning velocity to measured/predicted flame strain rate
- Compare directly to measured strain rates and laminar burning velocities

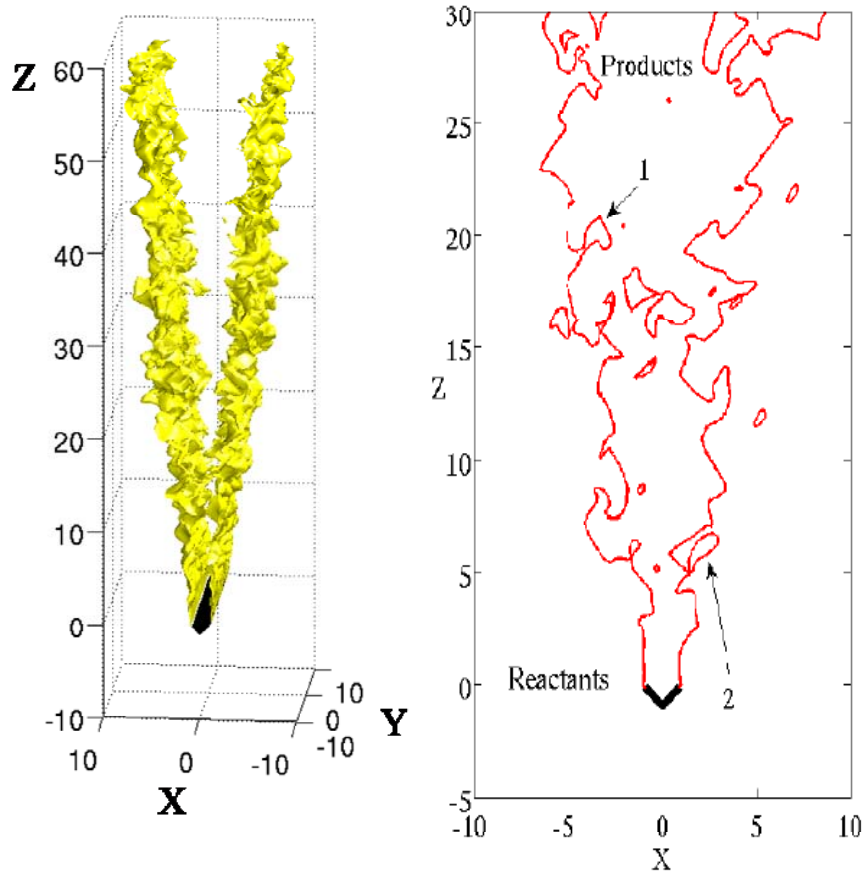


Modeling of Flame Characteristics

- Develop model for flame curvature and turbulence intensity at the flame leading points
- Perform analysis using level set equation:

$$\frac{\partial G}{\partial t} + \left(\vec{u}_f + s_L \vec{n}\right) \cdot \nabla G = 0$$

- Will be used to relate local flame curvature and turbulence intensity to quantities such as turbulence intensity, integral length scale, etc.



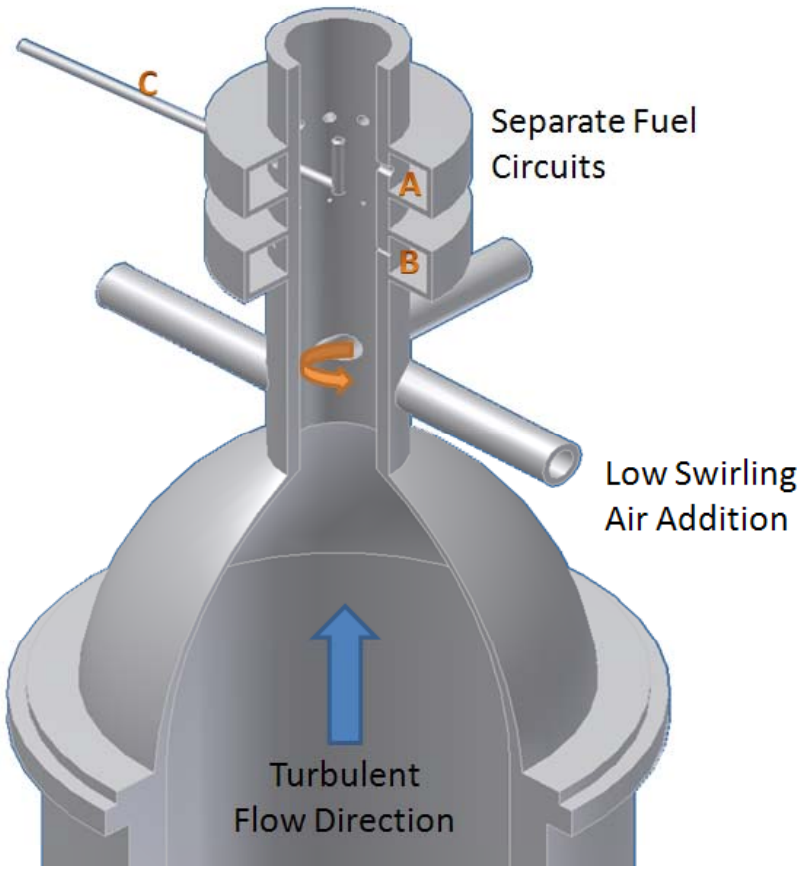
Turbulent Flame Propagation of Stratified Mixtures

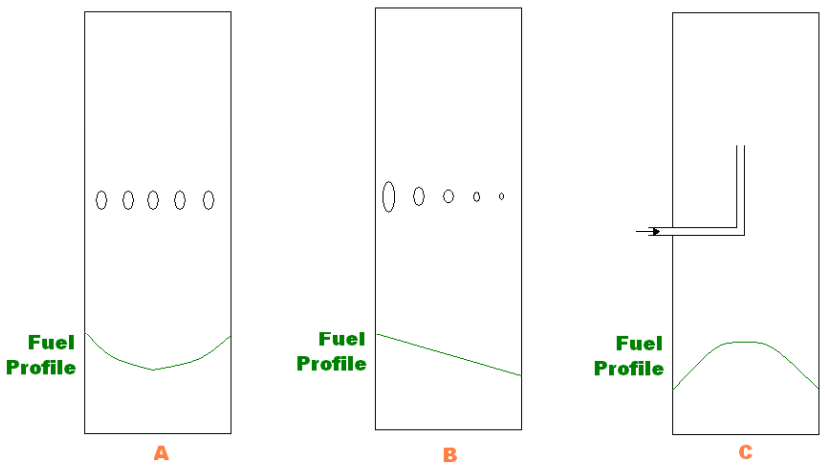
- Develop understanding of flame propagation in highly inhomogeneous flows

- Is local flame propagation in an inhomogeneous mixture parameterized by local flame propagation in a homogenous mixture with the same local properties?
  - Or do the derivatives of local properties affect flame propagation?

- Determine how local flame propagation is affected by gradients in mixture properties (i.e. $d\varphi/dr$, $d^2\varphi/dr^2$)
  - Create flows where:
    - $d\varphi/dr \neq 0$, $d^2\varphi/dr^2 \approx 0$
    - $d\varphi/dr \approx 0$, $d^2\varphi/dr^2 \neq 0$

Variable ϕ Profile Generator





Status Updates

- Obtained turbulent global consumption speed data for various H_2/CO ratio flames at 5 atm for 20-50 m/s mean flow velocities
- Designed and fabricated new LSB nozzle
- Developed design for facility modifications to allow for easy switching between Bunsen and LSB configurations

Future Work

- Implement facility design modifications to existing high pressure experimental facility
  - Will reuse many aspects of current facility in the new LSB experimental configuration
  - Versatile design to enable both experiments (Bunsen and LSB) to remain active without extensive configuration changes between experiments
- Perform initial experimental testing and validation of LSB in open, atmospheric configuration
  - CH_4/air and H_2/CO/air mixtures