Ben T. Zinn
Combustion Laboratory

Turbulent Flame Speed Measurements and Modeling of Syngas Fuels

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Motivation

- Ability to operate gas turbines safely and reliably with coal derived, syngas fuels
- Issues:
  - Turbulent flame speed, S_T, is a key combustion parameter that impacts the performance of low emissions combustion systems
    - Blowoff
    - Flashback
    - Combustion instabilities
    - Emissions

Motivation: Fuel Effects

Ref: Wu, M.-S. *et al*. Comb Sci. and Tech. Vol. 73 1990

H_2/air, Φ = 1.0,
$S_{L,0}$ = 2 m/s,
Re = 20,000

H_2/air, Φ = 3.57,
$S_{L,0}$ = 1.9 m/s,
Re = 20,000

Objective

- Obtain turbulent flame speed data of syngas fuel blends at gas turbine realistic conditions and over a range of conditions

- Develop physics-based scalings and analyses to predict turbulent flame speed dependencies across broad fuel space

Presentation Summary

- Facility
  - Burner
  - Turbulence generator
  - Pressure vessel
- Velocity Characterization using LDV
  - Mean and RMS profiles
  - Performance characteristics
- Reacting Flow Studies
  - Flame Imaging
  - $S_{T,GC}$ trends
- Discussion and Analysis
  - Leading points modeling

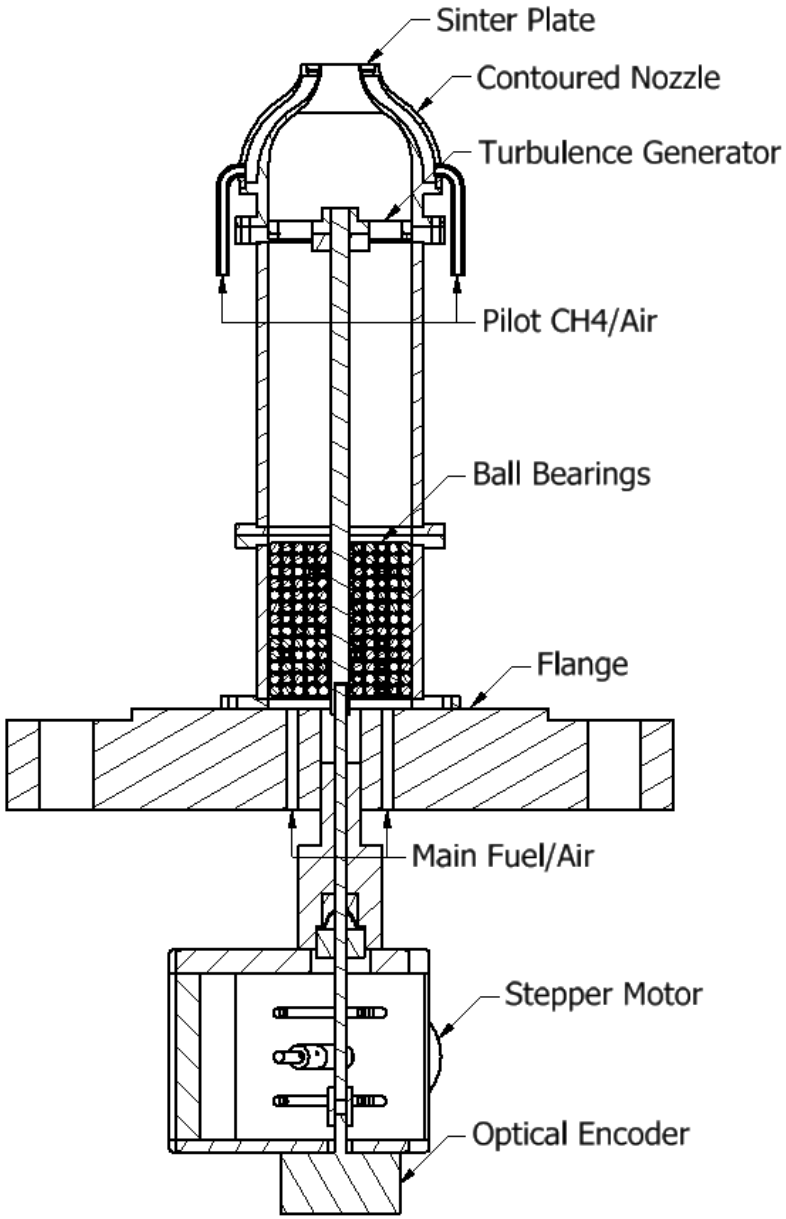
Facility

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
      - Quantified here using Bunsen flame technique
    - $S_{T,LC}$ – Local consumption speed
    - $S_{T,GD}$ – Global displacement speed
    - $S_{T,LD}$ – Local displacement speed
      - LSB facility has been fabricated and is nearly operational

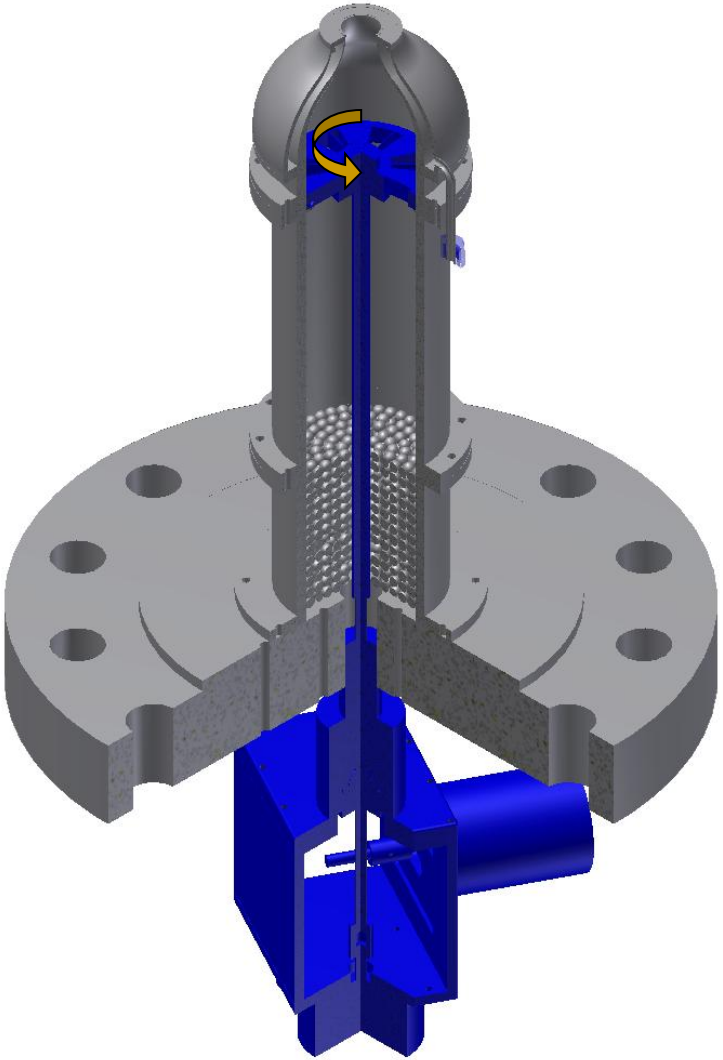
Burner

- Piloted Bunsen flame
  - Contoured nozzle
  - Annular pilot flame to stabilize the main flame
    - Tested at exit velocities from 4-70 m/s
- Multiple diameters to assess length scale effects



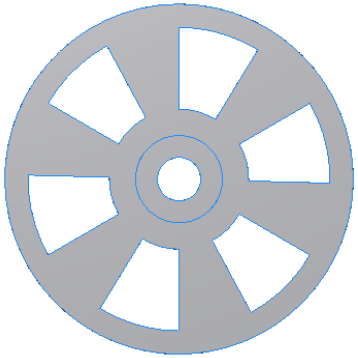
Variable Turbulence Generator

- Design developed to meet the following requirements:
  - Variable turbulence intensity without changing out plates or changing velocity
  - Wide range of turbulence intensities
  - “Clean” exit profiles of mean and turbulent quantities
- Remotely controlled system to vary the turbulence intensity
  - Critical capability for operation in pressure vessel

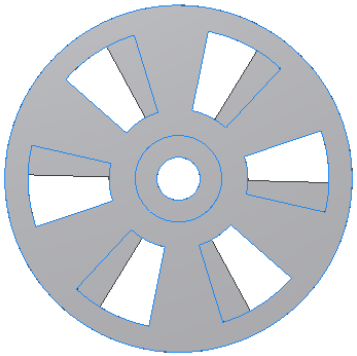


Turbulence Generator – Variable Blockage Plates

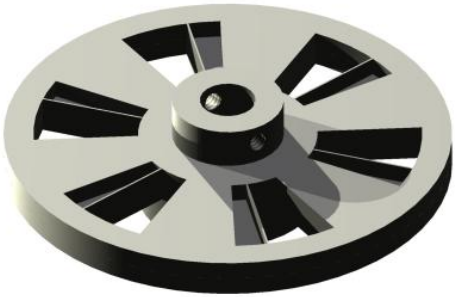
- Based upon previously developed azimuthal slot approach
  - Videto and Santavicca (1991)
  - Bédat and Cheng (1995)
  - Variable operation required radial slots



Fully Open



Partially Open



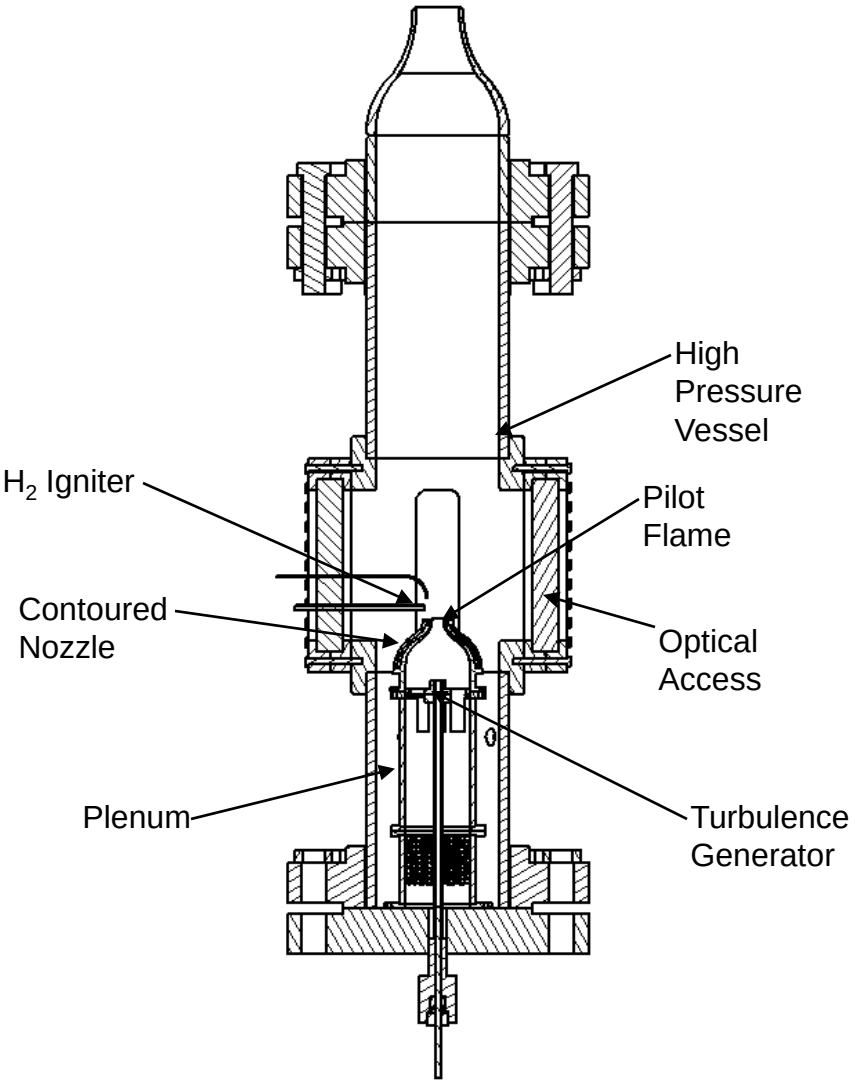
Top View

Bottom View

Bédat, B., Cheng, R. K., Combustion and Flame, 1995
Videto, B.D., Santavicca, D. A., Combustion Science and Technology, 1991

High Pressure Facility

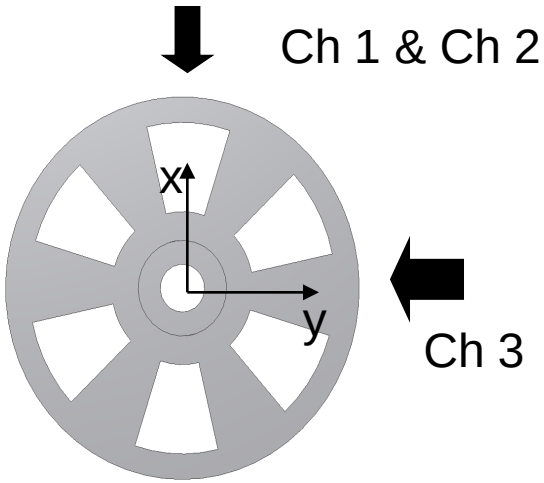
- Pressure vessel
  - Up to 20 atm
  - Optical access for diagnostics
  - Cold and pre-heated flow
- Diagnostics
  - Laser Doppler Velocimetry
  - Hot-wire anemometry
  - Chemiluminescence
  - CH and OH PLIF
- Fully remotely operable

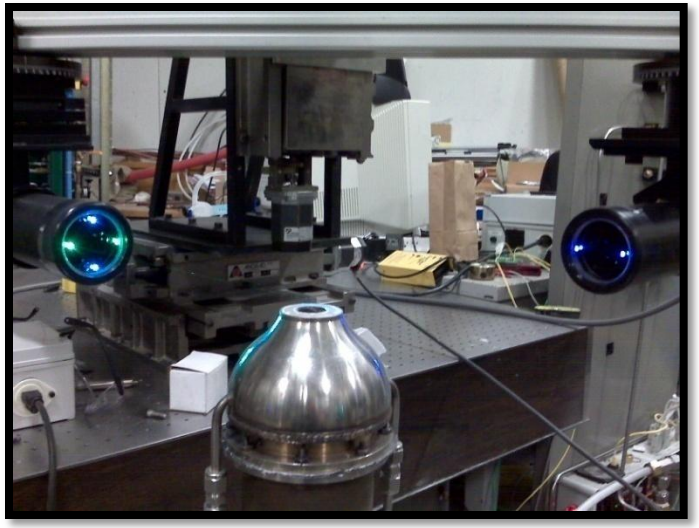


Velocity Characterization

LDV Characterization

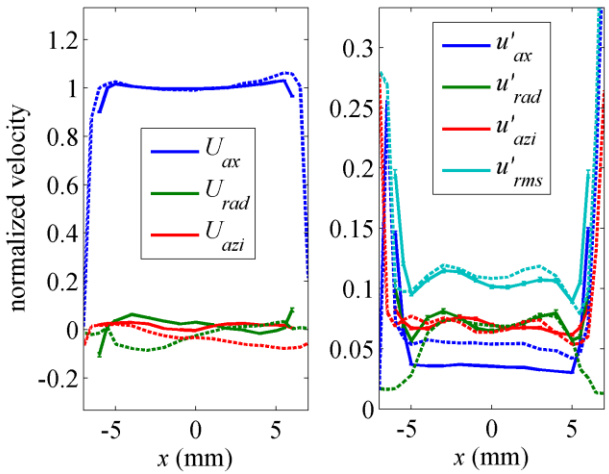
- LDV performed for wide range of operating conditions
  - D = 12 and 20 mm
  - p = 1-20 atm
  - T = 300-500 K
  - U_0 = 4-50 m/s
- Quantified 3-D mean and turbulence profiles in two cuts
  - Cuts aligned over slot and solid portion



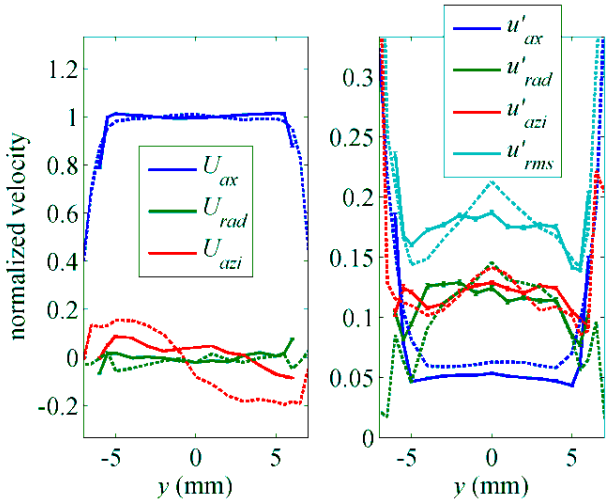


Mean and RMS Profiles

- Observations:
  - Uniform mean axial profile
  - Uniform turbulence profiles except in boundary layer
- High turbulence intensities (> 10 m/s achievable)



BR = 69%



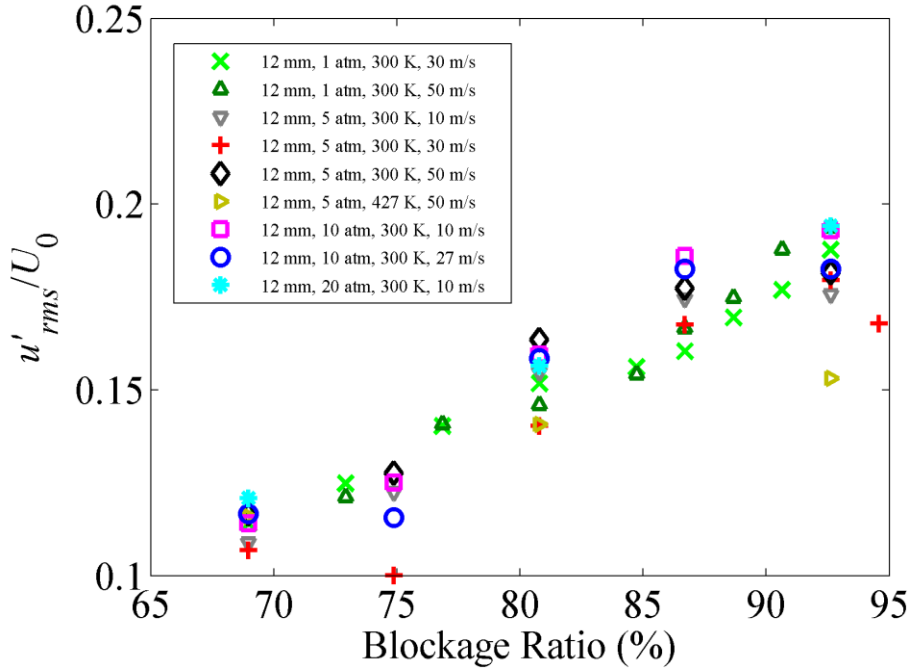
BR = 93%

Dashed and solid lines correspond to 1 and 5 atm, respectively

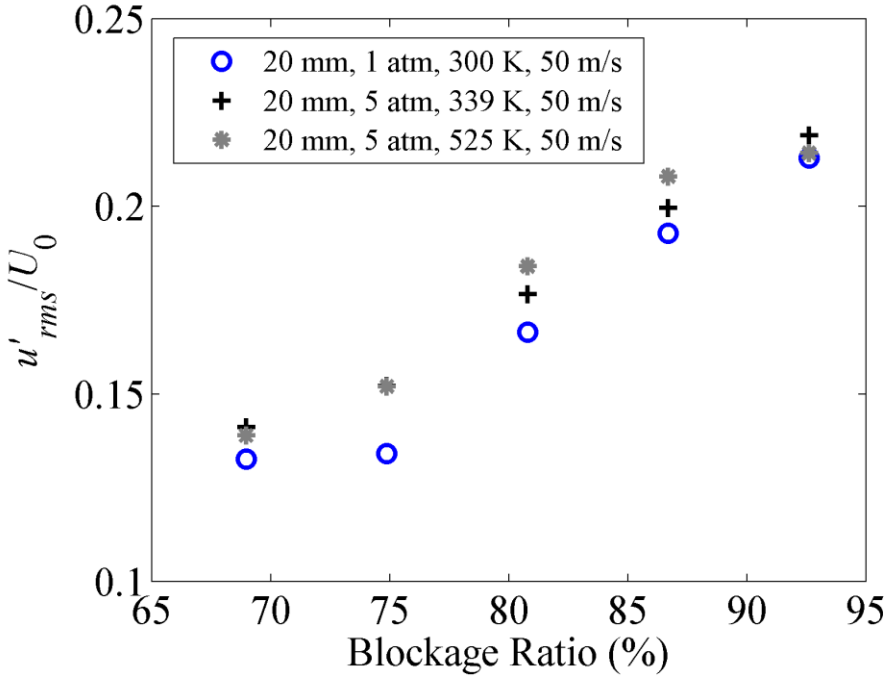
T = 300 K, U_0 = 30 m/s

Performance Characteristics

12 mm



20 mm



- Turbulence intensities of ~10-25% achievable

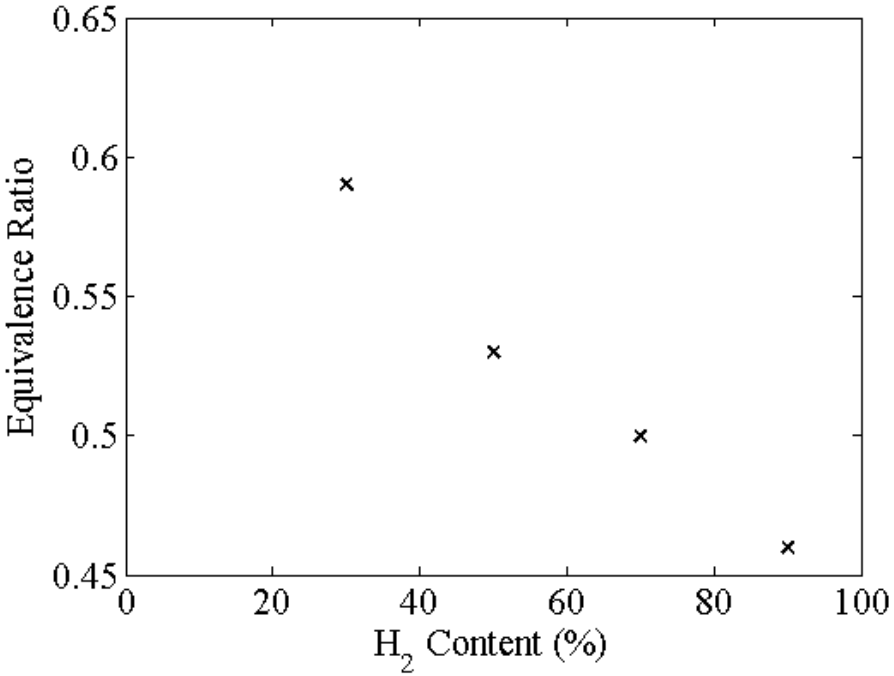
Reacting Flow Studies

Overview

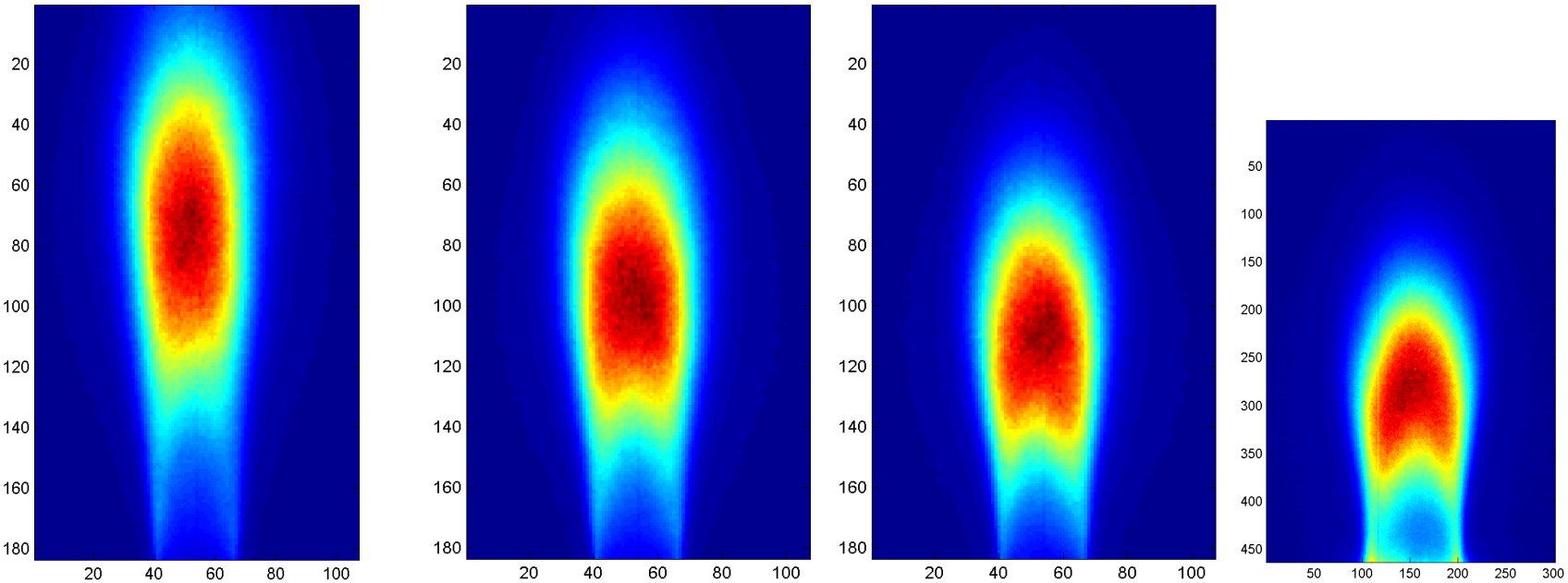
- Flame speed data acquired at the following conditions:
  - Burner diameters: 12 and 20 mm
  - Chamber pressures: 1 and 5atm
  - Preheat Temperatures: 300 and 600 K
  - Bulk velocity: 4-50 m/s
  - H_2/CO mixtures (30-90% H_2) and CH_4
  - Equivalence ratios : 0.4-0.8

Design of Experiments Approach

- Constant $S_{L,0}$ studies: Vary H_2 percentage and equivalence ratio simultaneously
- Constant H_2/CO ratio studies: Sweep equivalence ratio
  - 60% H_2 : Φ = 0.4, 0.6 and 0.8
  - 30% H_2: Φ = 0.59, 0.7 and 0.8



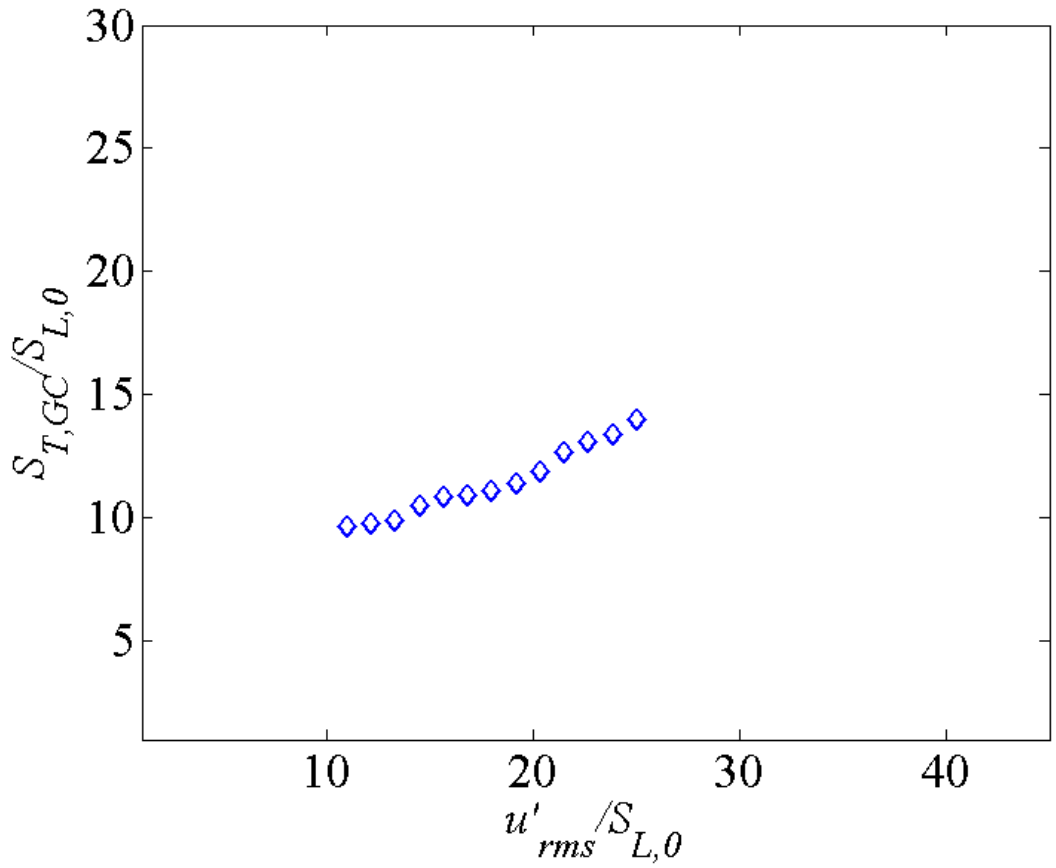
H_2 Content Effect (Fixed $S_{L,0}$=34 cm/s)



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

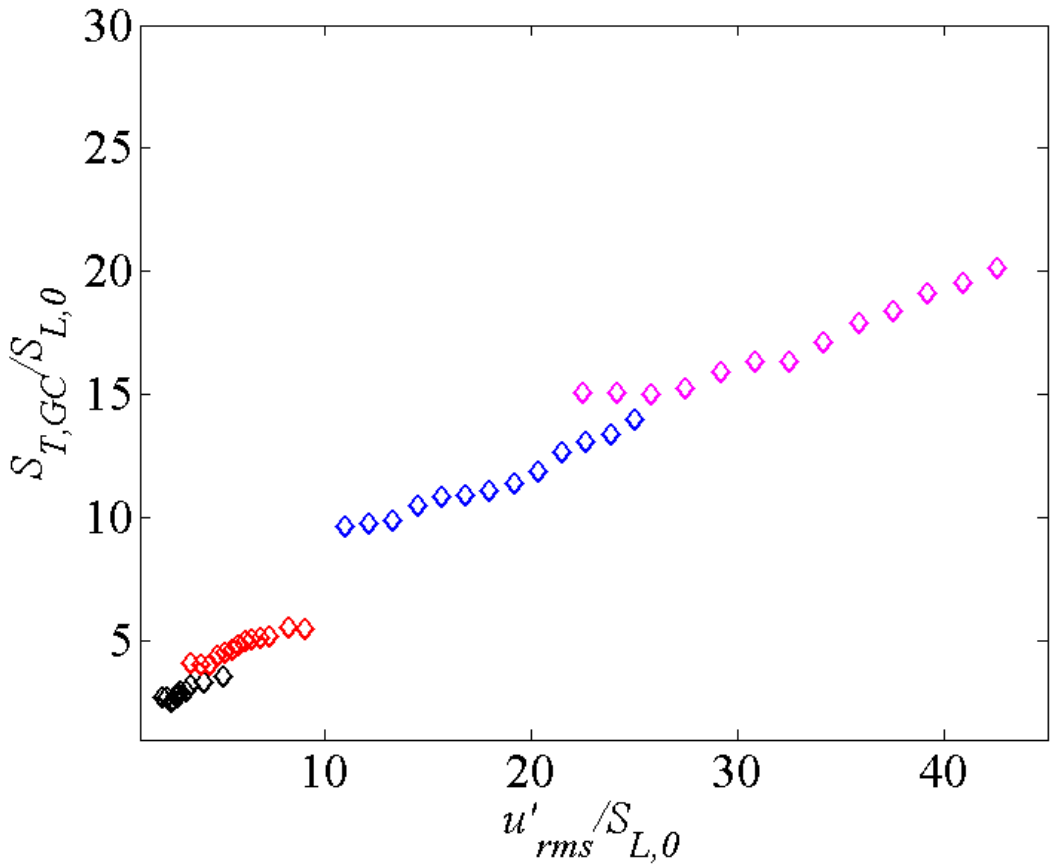
- Clear increase in $S_{T,GC}$ observed at constant $S_{L,0}$ as H_2 % increases
  - Not a low $u'/S_{L,0}$ effect (= 45 in this data)
  - U_0 = 50 m/s, u'/U_0 = 19.2%

Flame Speed Data – Typical Results



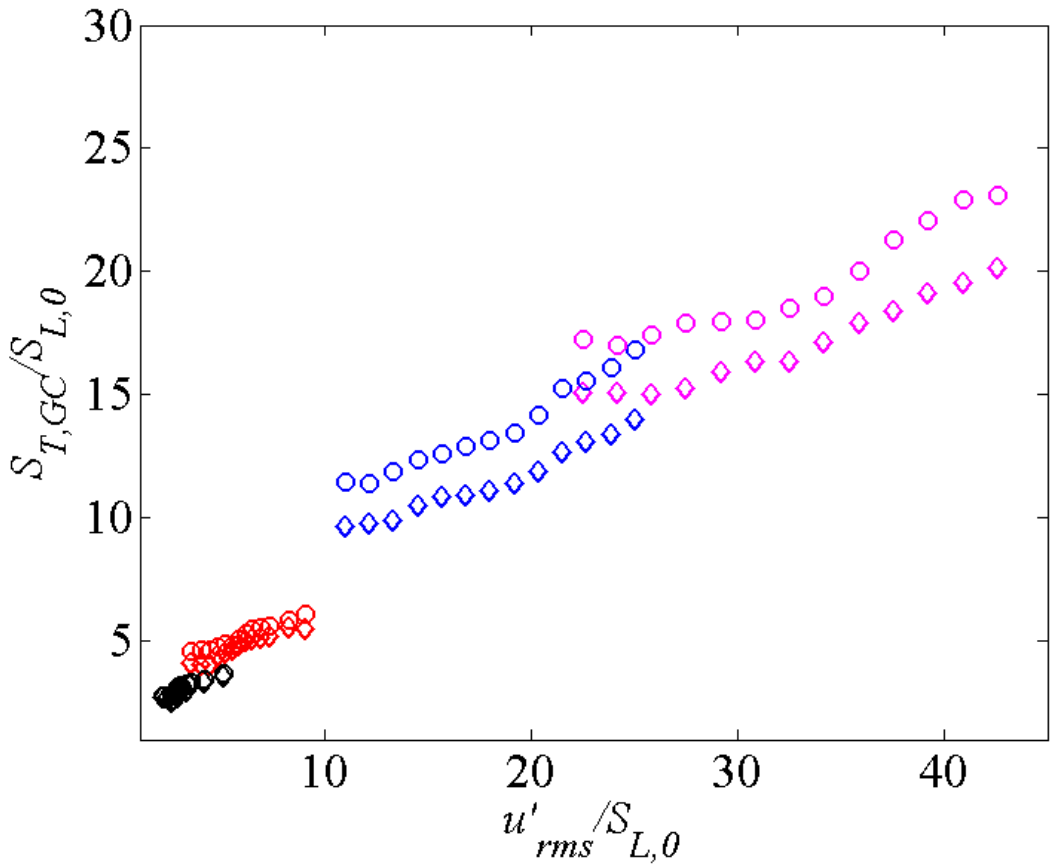
- U_0 = 30m/s, H_2 content = 30%, $S_{L,0}$ = 34 cm/s

Flame Speed Data – Varying U_0



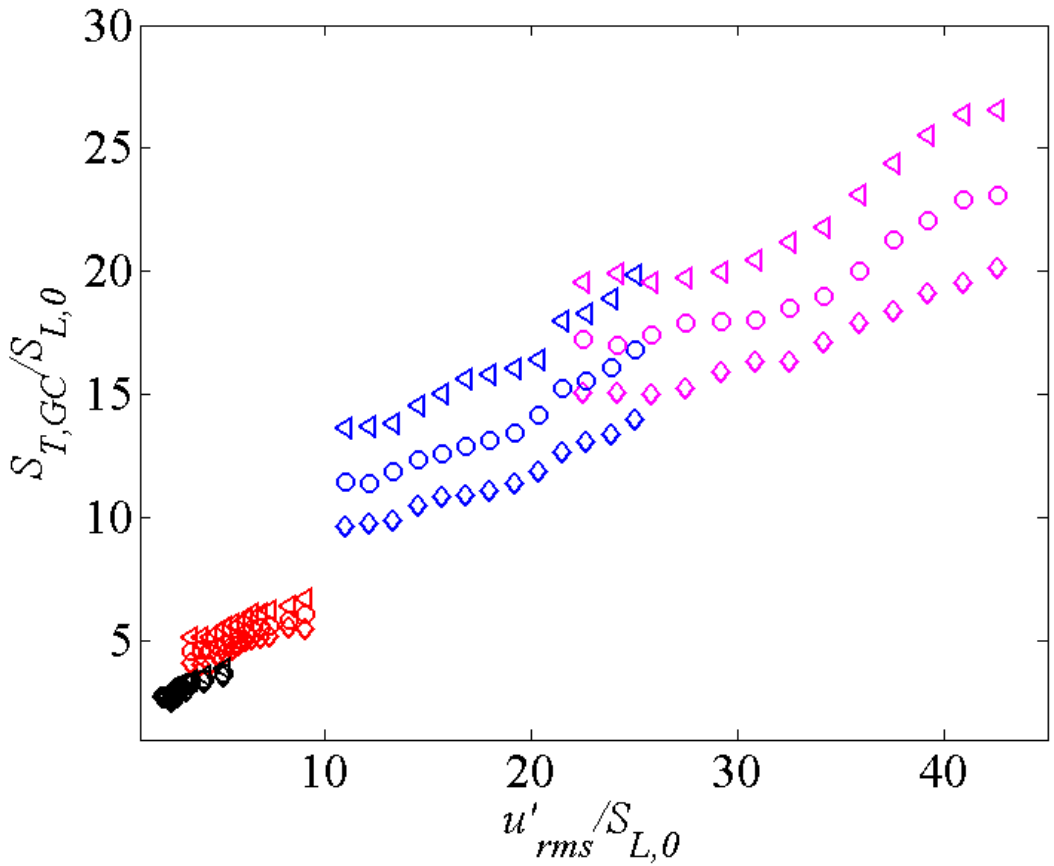
- U_0 = 4 - 50m/s, H_2 content = 30%, $S_{L,0}$ = 34 cm/s

Flame Speed Data – Varying H_2/CO Ratio



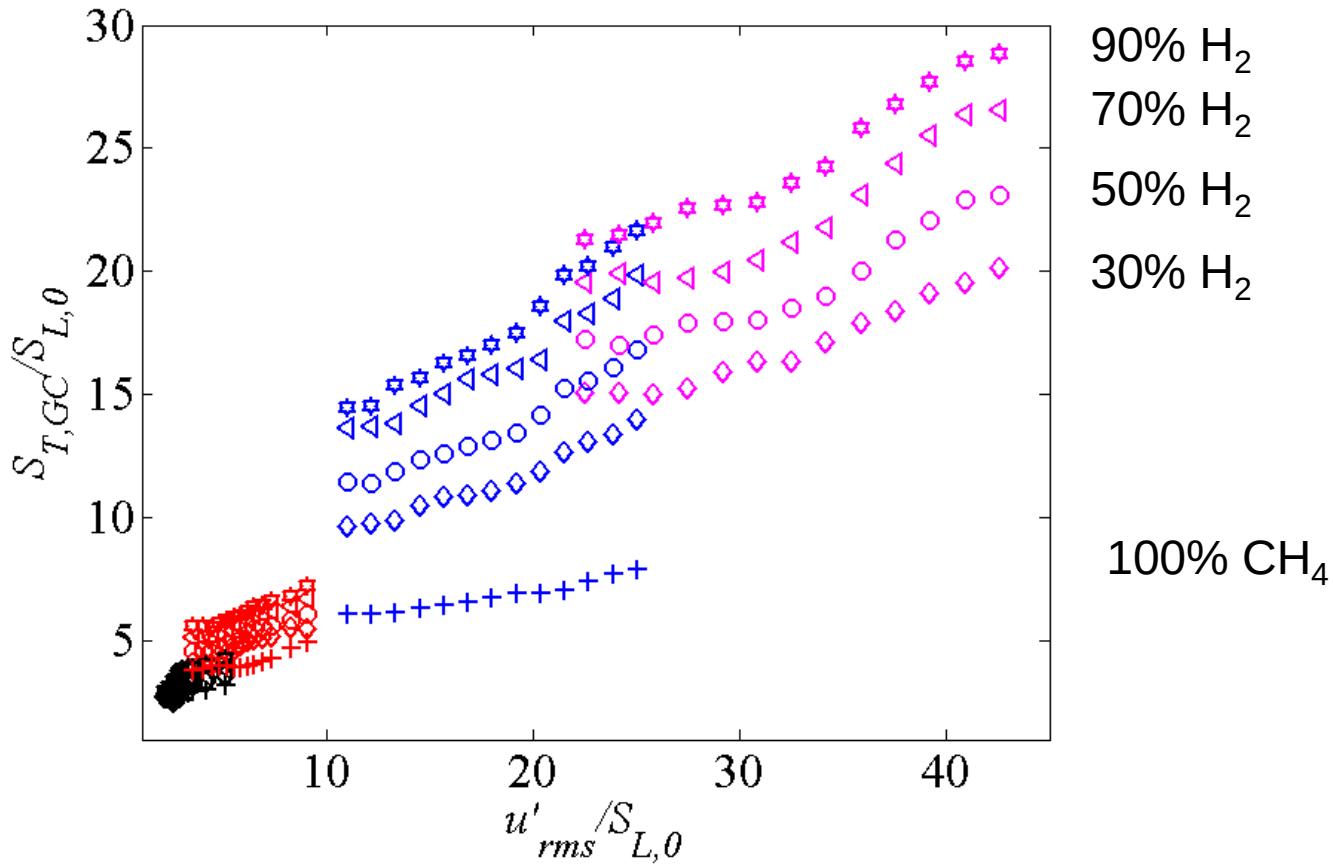
- U_0 = 4 - 50m/s, H_2 content = 30, 50%, $S_{L,0}$ = 34 cm/s

Flame Speed Data – Varying H_2/CO Ratio



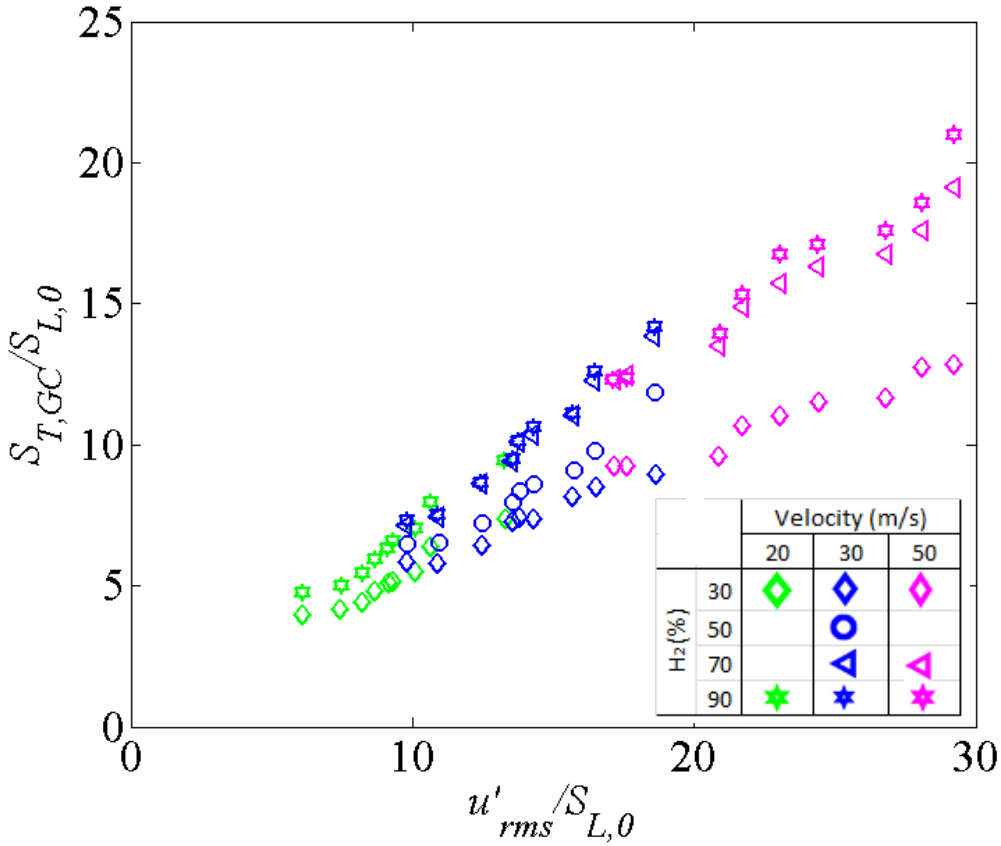
- U_0 = 4 - 50m/s, H_2 content = 30 - 70%, $S_{L,0}$ = 34 cm/s

Flame Speed Data – Varying H_2/CO Ratio



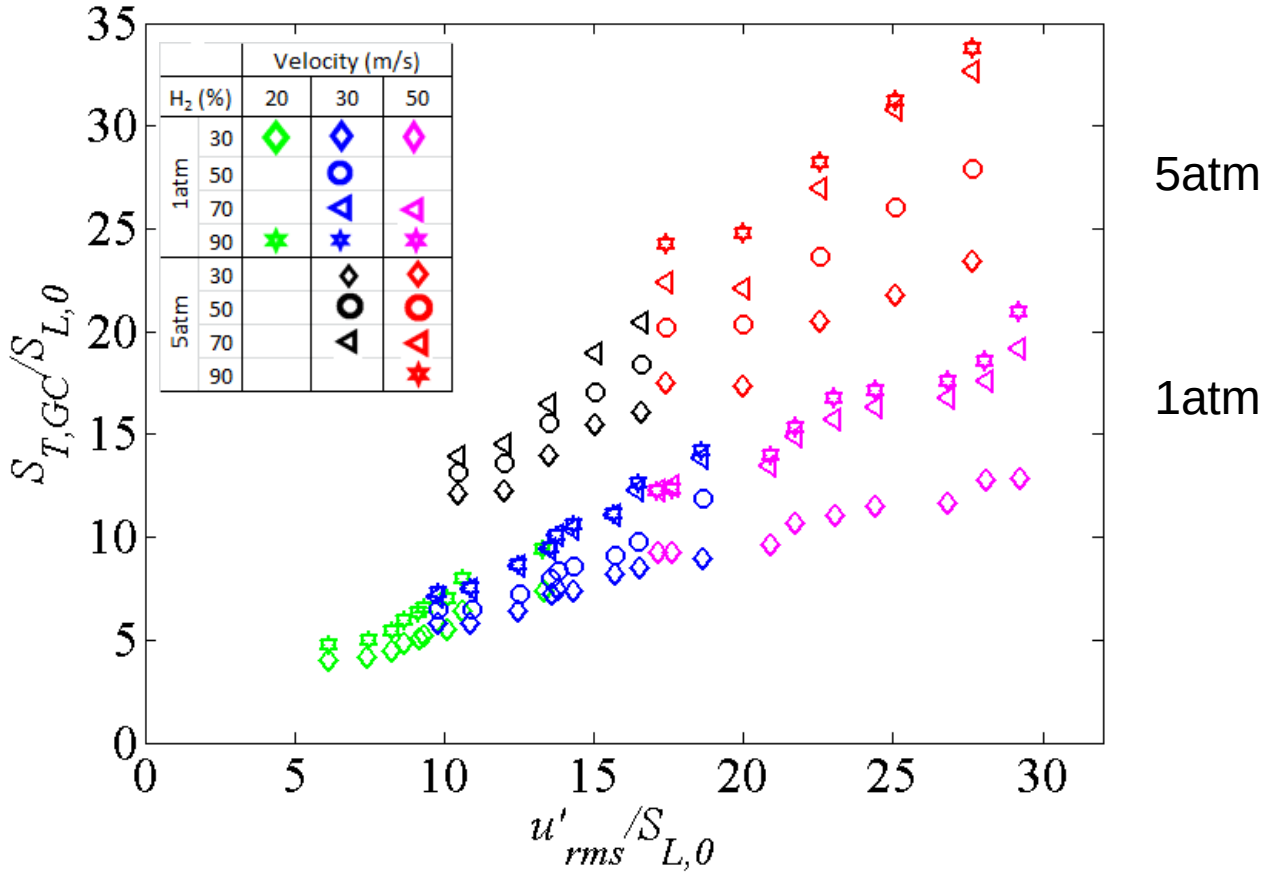
- U_0 = 4 – 50 m/s, H_2 = 30% - 90%, $S_{L,0}$ = 34 cm/s
- Data shows clear increase of $S_{T,GC}$ with H_2 content at fixed $S_{L,0}$

Constant $S_{L,0}$ – 12 mm Burner



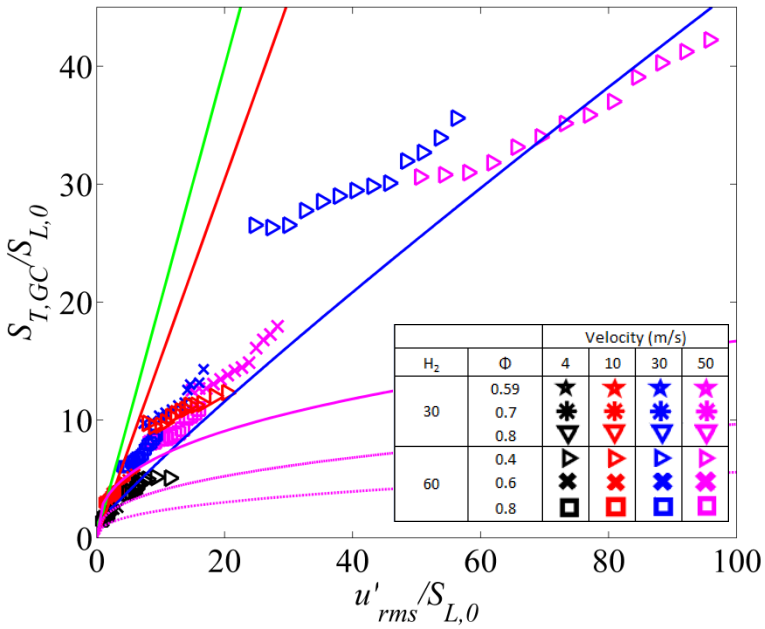
- U_0 = 20-50 m/s, H_2 = 30-90%, $S_{L,0}$ = 34 cm/s
- Data generally shows increase of $S_{T,GC}$ with H_2 content at fixed $S_{L,0}$
  - Weaker dependence than with 20 mm
- For fixed conditions, larger burner diameter results in larger $S_{T,GC}$

Constant $S_{L,0}$ – 12 mm Burner, Pressure Effects

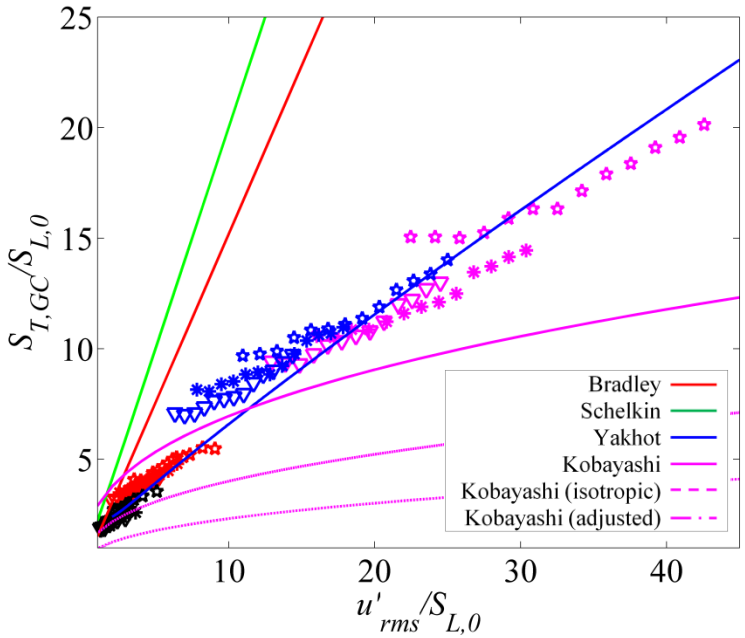


- At the same U_0, H_2/CO ratio and $S_{L,0}$, factor of 5 increase in pressure → factor of 2 increase in $S_{T,GC}$

Flame Speed Data – Varying Φ



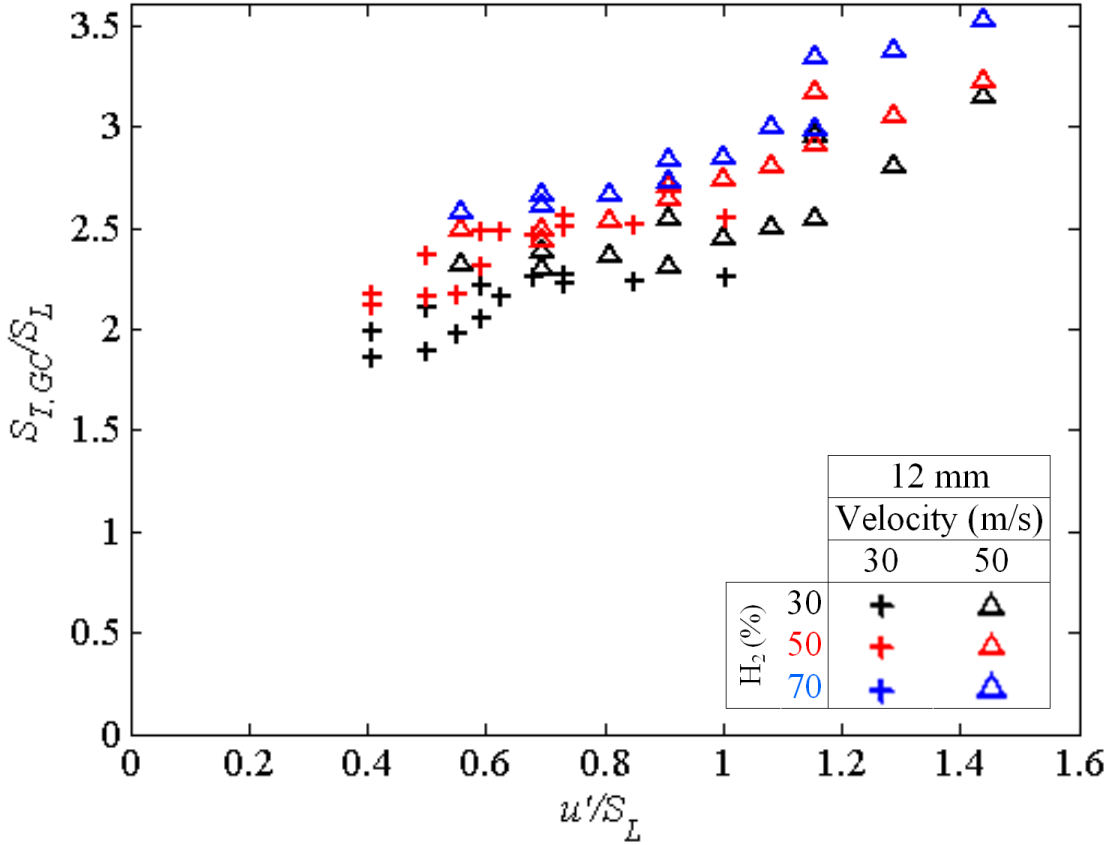
60% H_2



30% H_2

- Φ varied while H_2/CO ratio held constant
- Data at $u'/S_{L,0}$ ranges of interest for gas turbine designers

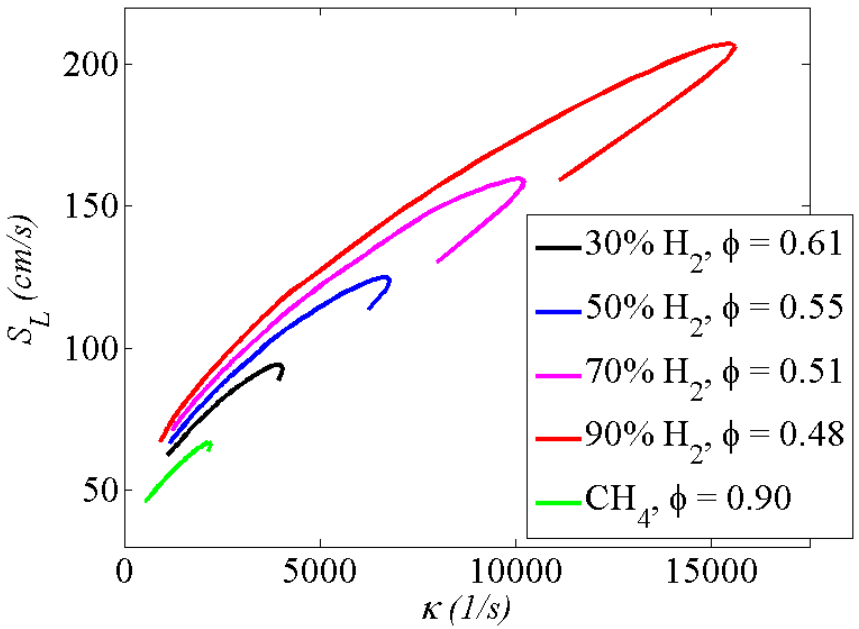
Flame Speed Data – Preheat

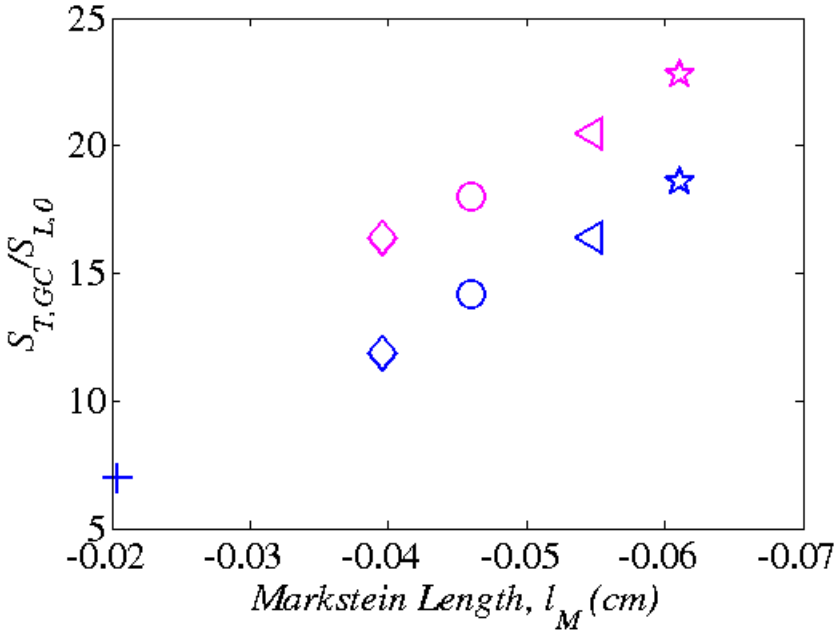


- U_0 = 30-50 m/s, D = 12 mm, T_u = 600 K, H_2 = 30-90%, $S_{L,0}$ = 200 cm/s
- Low $u'/S_{L,0}$ because of very high flame speed
- Data shows clear increase of $S_{T,GC}$ with H_2 content at fixed $S_{L,0}$

Scaling and Physics-Based Modeling

Observations





- Results consistent with general trend seen in literature that $S_{T,GC}$ increases with stretch sensitivity of reactants

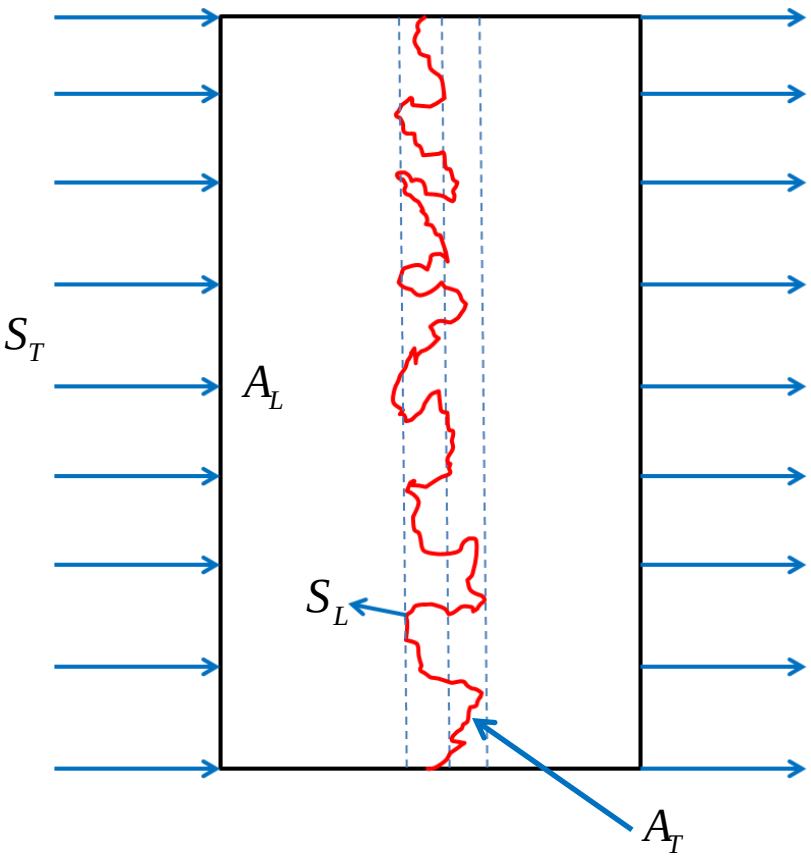
Flame Speed Scaling-Consumption Based Approaches

- Common approach for scaling turbulent flame speeds based on the consumption speed approach:

$$S_T = \frac{\langle S_L A_T \rangle}{A_L}$$

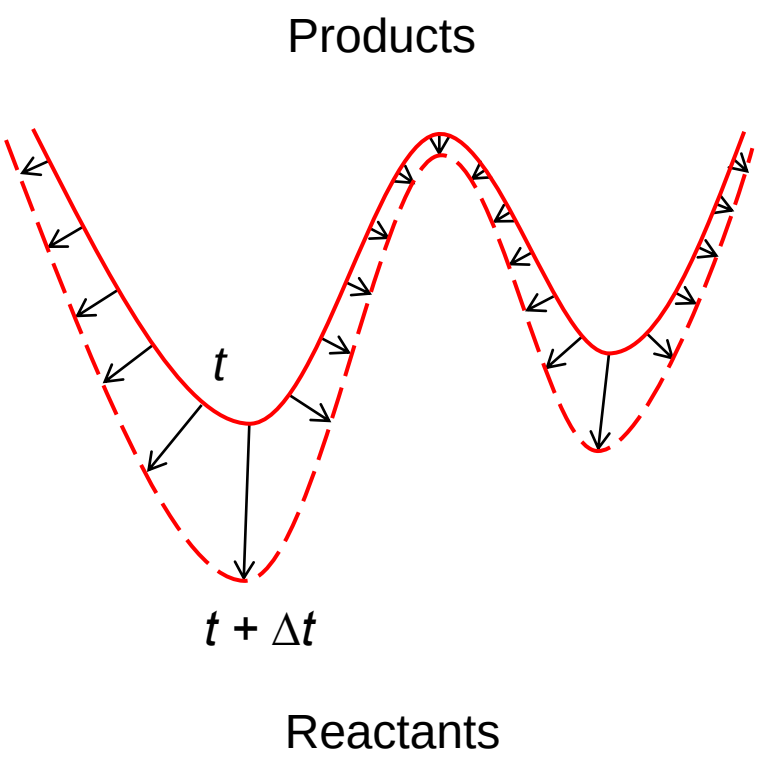
- Can be modified to include the stretch factor, I_0, where $I_0 = S_L / S_{L,0}$:

$$S_T = \frac{S_{L,0} \langle I_0 A_T \rangle}{A_L}$$



Flame Speed Scaling – Leading Points Approaches

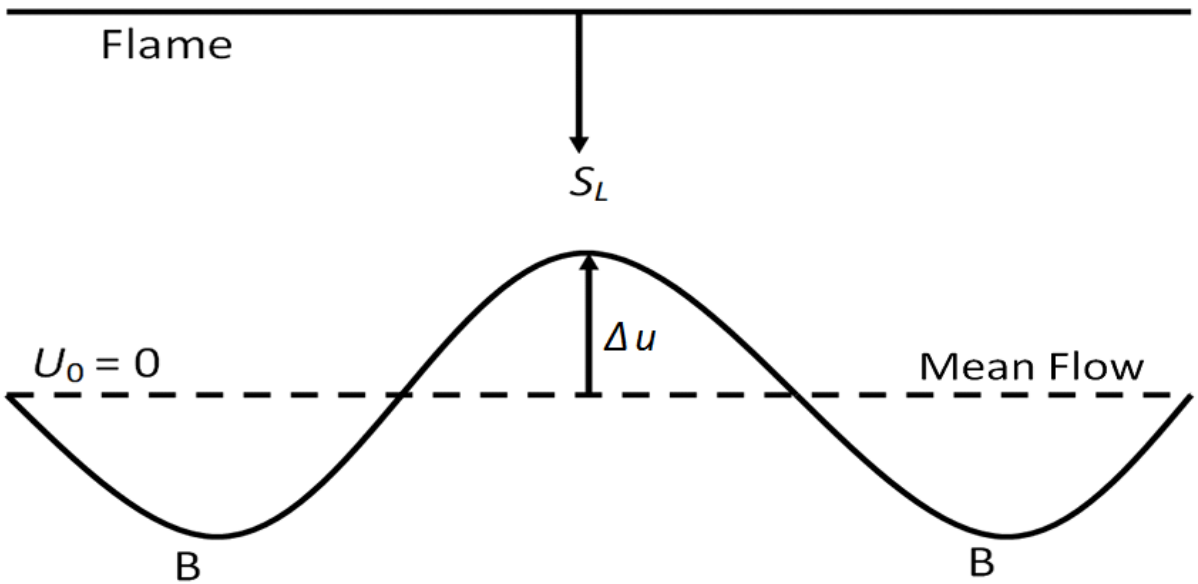
- Local flame speed and area are highly correlated
  - Difficult to show physics from "global" modeling approaches
- *Local*, leading points modeling approaches are useful for explicitly bringing out stretch sensitivity effects.
  - Leading points - positively curved points on the turbulent flame front that propagate out farthest into the reactants (Kuznetsov *et al.* 1986, Lipatnikov *et al.* 2005, Karpov *et al.* 1997)



A.N. Lipatnikov, J. Chomiak, Progress in Energy and Combustion Science 31 (1) (2005) 1–73
V.R. Kuznetsov, V.A. Savel'nikov, Turbulence and Combustion, Hemisphere Publishing Corporation, (1986) 362
V.P. Karpov, A.N. Lipatnikov, V.L. Zimont, Avances in Combustion Science, AIAA, (173), (1997) 235-250

Significance of Leading Points-Model Problem

- Consider the following model problem
  - Flat flame propagating into a non-uniform flow of mean flow U_0 = 0 m/s, with amplitude of Δu

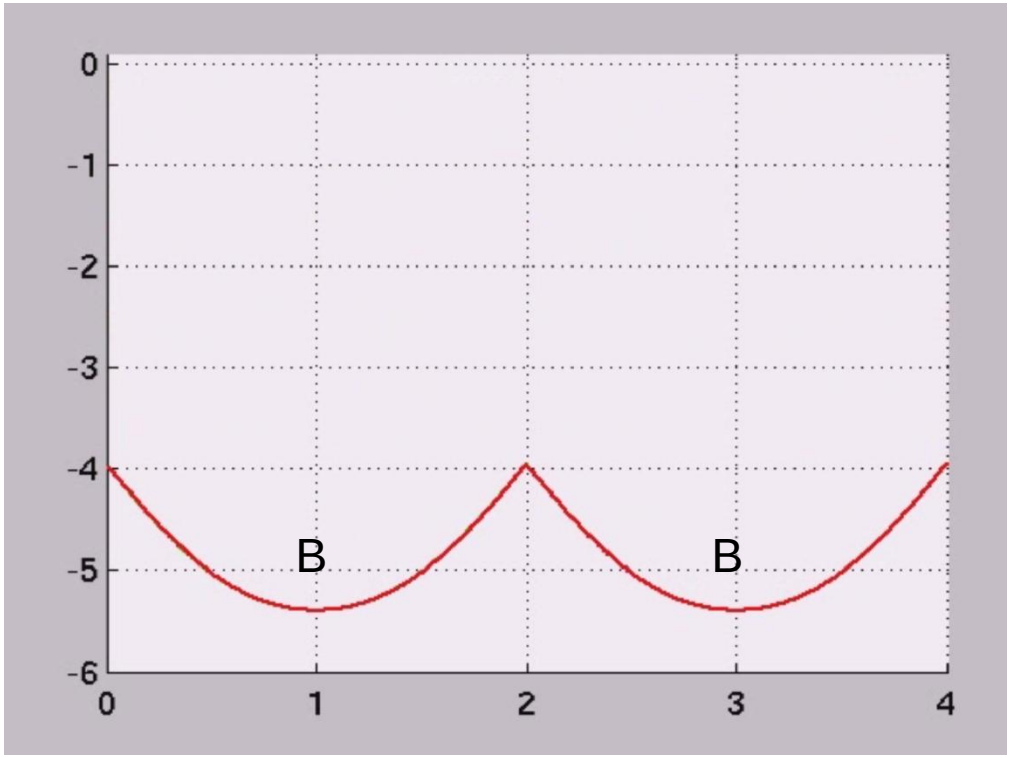


Significance of Leading Points-Model Problem

- At point B, where the mean flow is slowest, the flame front propagates farthest – leading point
- The displacement speed at B is:

$$S_D = S_L + (\Delta u)_{LP}$$

- Shows that increase in flame area *is the effect, not the cause* of increased flame speed
  - Rather flame speed controlled by propagation speed of leading points



Displacement Speed Scaling

- Through flame curvature and preferential diffusion the flame speed is modified at the leading point
- Average displacement speed at the leading point

$$S_D = \langle S_L \rangle_{LP} + \langle u' \rangle_{LP}$$

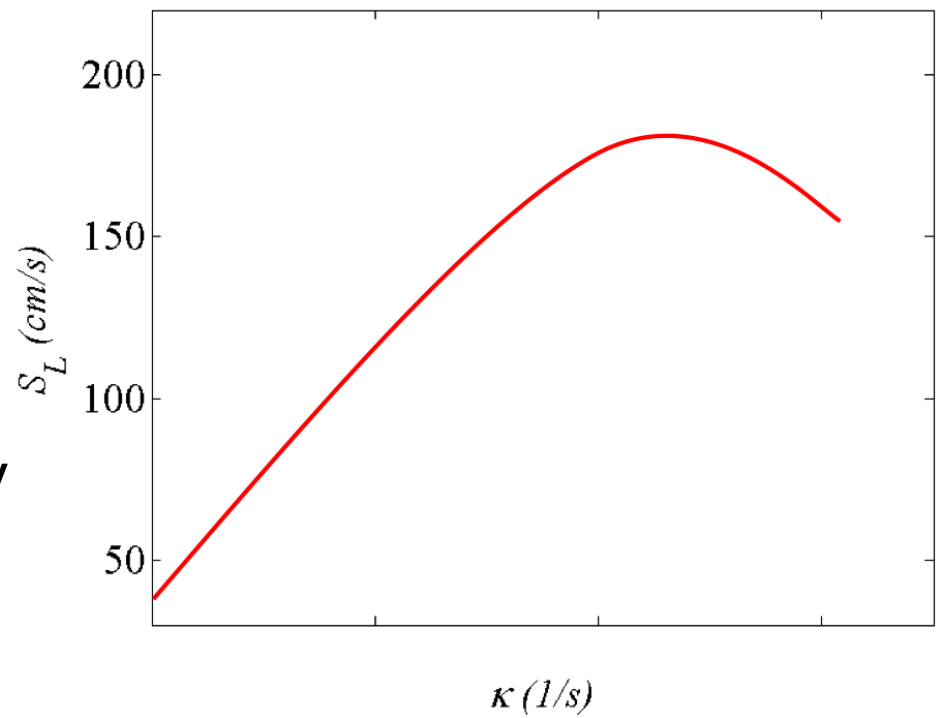
Where:

$\langle S_L \rangle_{LP}$ = laminar flame speed at the leading point due to pref. diffusion

$\langle u' \rangle_{LP}$ = turbulence intensity at the leading point

Scaling Flame Speed Augmentation

- Key problem lies in scaling $\langle S_L \rangle_{LP}$
  - Level set calculations to scale extrema statistics
  - Working with Bell, Day and Cheng at LBNL to analyze their DNS results

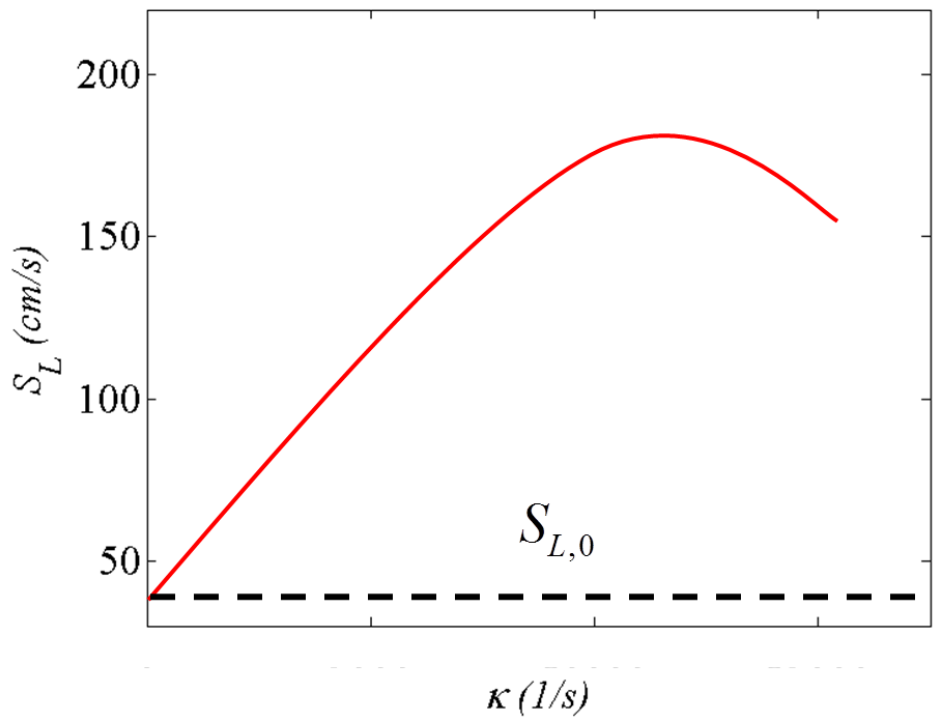


Scaling Flame Speed Augmentation

- Key problem lies in scaling $\langle S_L \rangle_{LP}$

- For Ma>0 reactants, can bound its value :

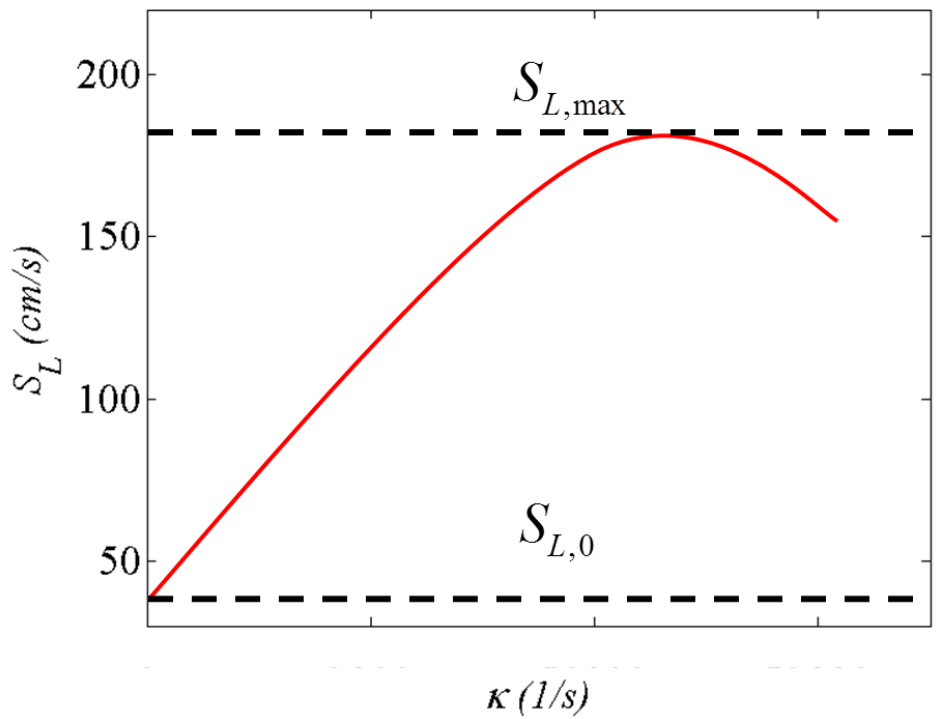
$$\langle S_L \rangle_{LP} > S_{L,0}$$



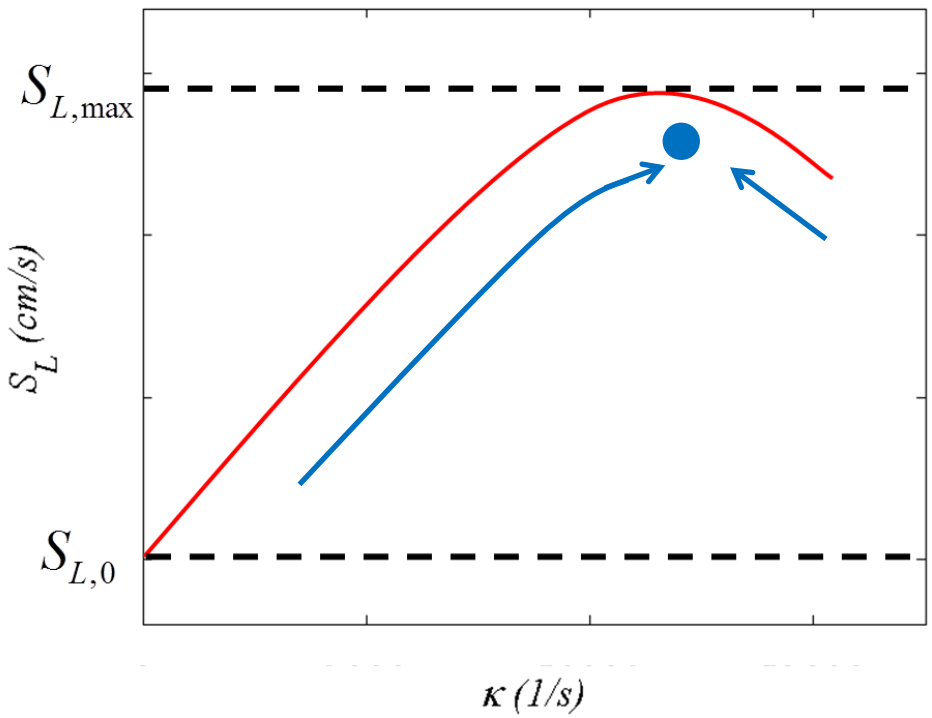
Scaling Flame Speed Augmentation

- Key problem lies in scaling $\langle S_L \rangle_{LP}$
- For Ma>0 reactants, can bound its value:

$$S_{L,\max} > \langle S_L \rangle_{LP} > S_{L,0}$$

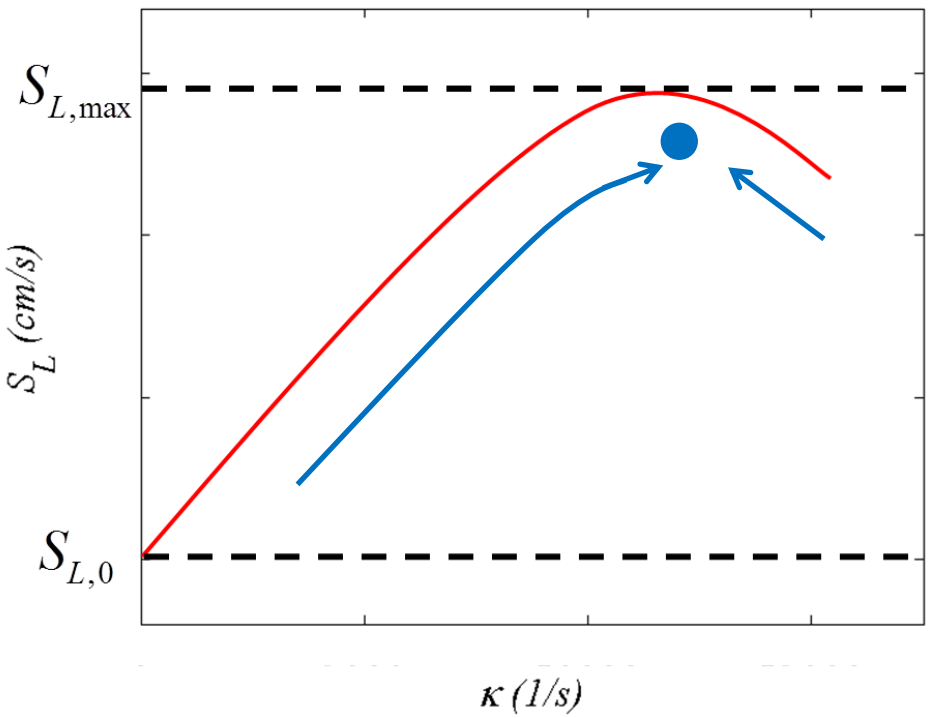


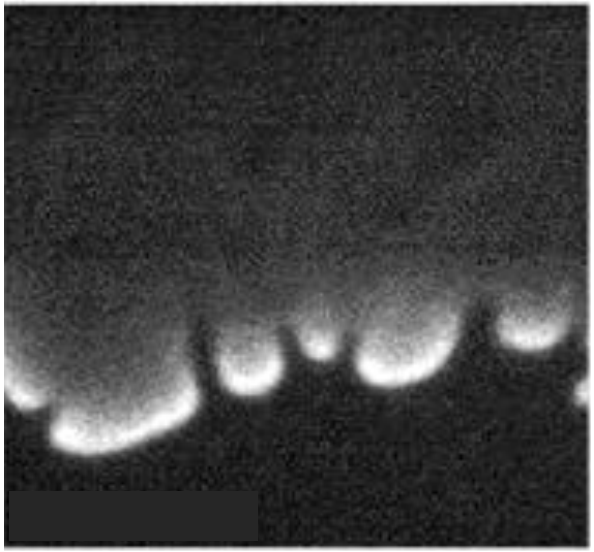
Scaling Flame Speed Augmentation



- Level set analysis of constant density flames:
  - Can show that $S_L = S_{L,max}$ is a steady state "attracting" point

Scaling Flame Speed Augmentation





H_2

Cheng R.K., *Turbulent Combustion Properties of Premixed Syngas*, in *Synthesis Gas Combustion: Fundamentals and Applications*, T. Lieuwen, V. Yang, and R. Yetter, Editors. 2010, CRC. p. 129-168.

Displacement Speed Inequality

- Equating $\langle S_L \rangle_{LP}$ to $S_{L,max}$ is appropriate in the 'quasi-steady' limit of slow turbulent fluctuations
- Leads to: $S_D \leq S_{L,\max} + \langle u' \rangle_{LP}$

$$\frac{S_D}{S_{L,max}} = 1 + \frac{\langle u' \rangle_{LP}}{S_{L,max}}$$

Quasi-Steady:
$\tau_{int} >> \delta / S_{L,ref}$

$$\frac{S_D}{S_{L,max}} \leq 1 + \frac{\langle u' \rangle_{LP}}{S_{L,max}}$$

$\tau_{int} \sim \delta / S_{L,ref}$

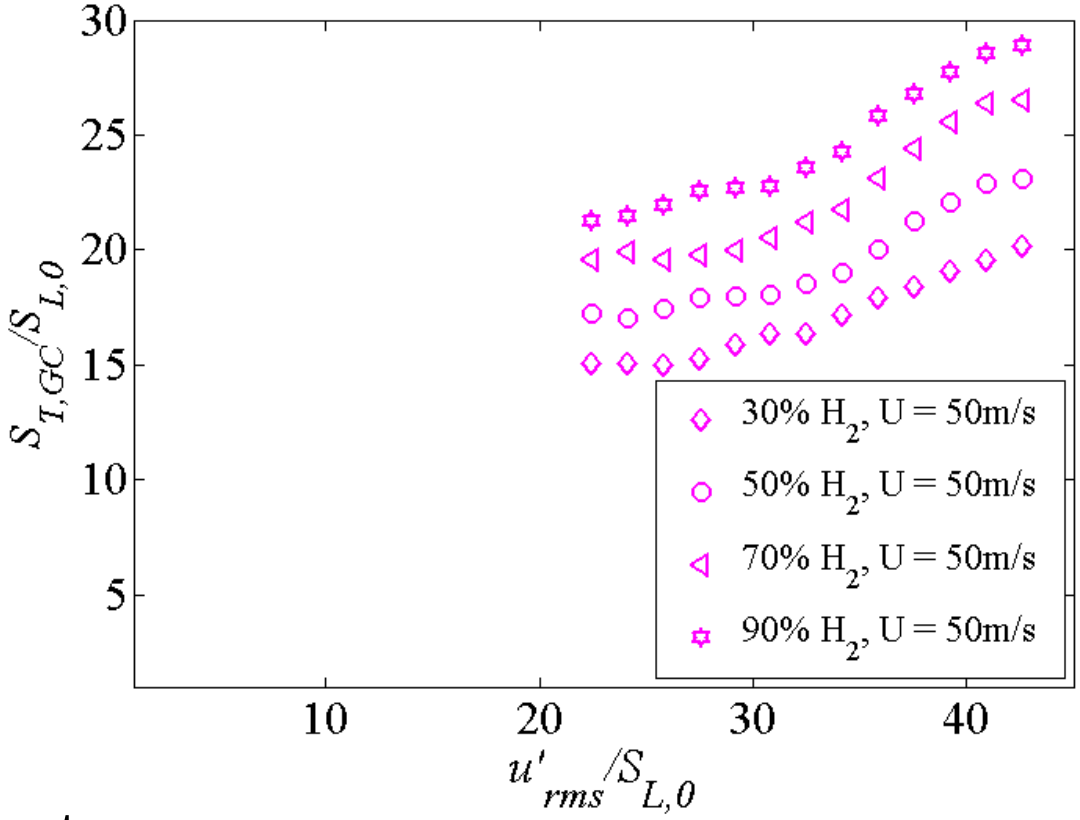
- Very similar to the Damköhler scaling except we are using $S_{L,max}$

Comments on $S_{L,max}$ Dependencies

- Suggests that $S_{L,max}$ is the natural dynamical parameter for scaling data
- $S_{L,max}$ is not an intrinsic property of the mixture
  - Burning velocity definition
  - Hydrodynamic strain vs. curvature induced flame stretch
  - Flow strain profile through flame; e.g.;
    - Nozzle separation distance in OPPDIFF
    - Potential flow vs. plug flow nozzle exit velocity profile
  - Non quasi-steady chemistry for unsteady problems

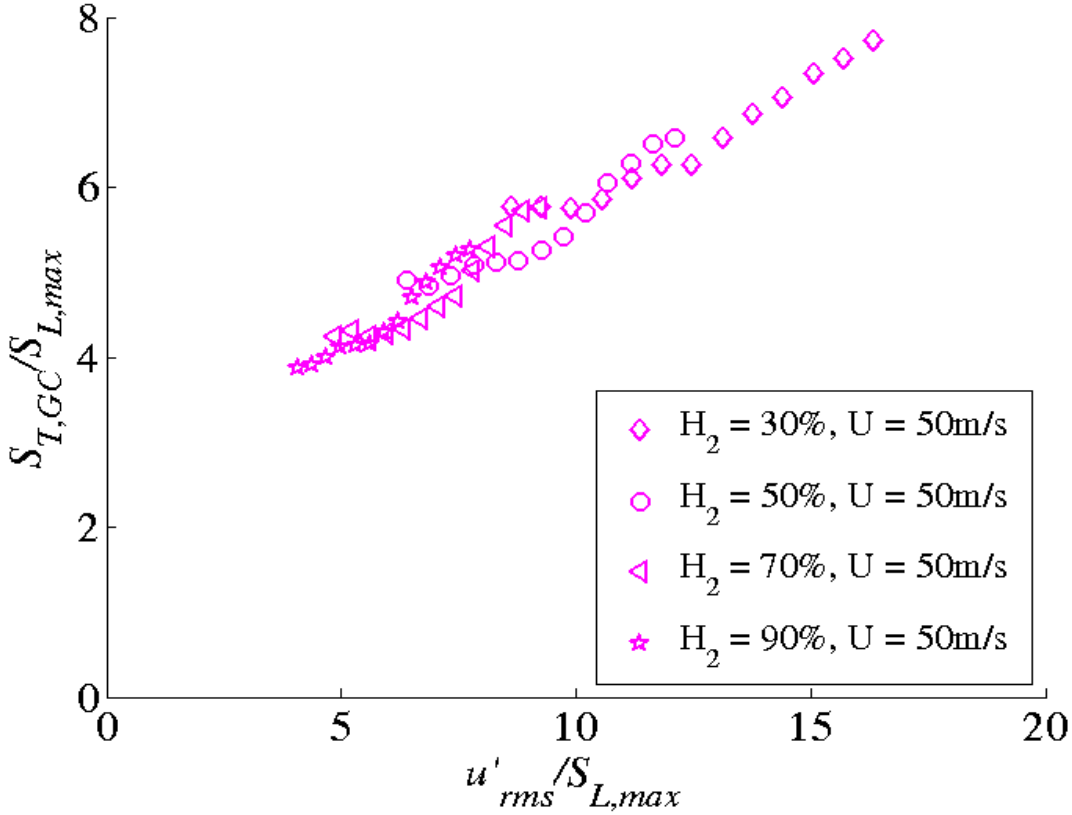
Data Analysis using $S_{L,max}$ concepts

Normalization Results – 50 m/s



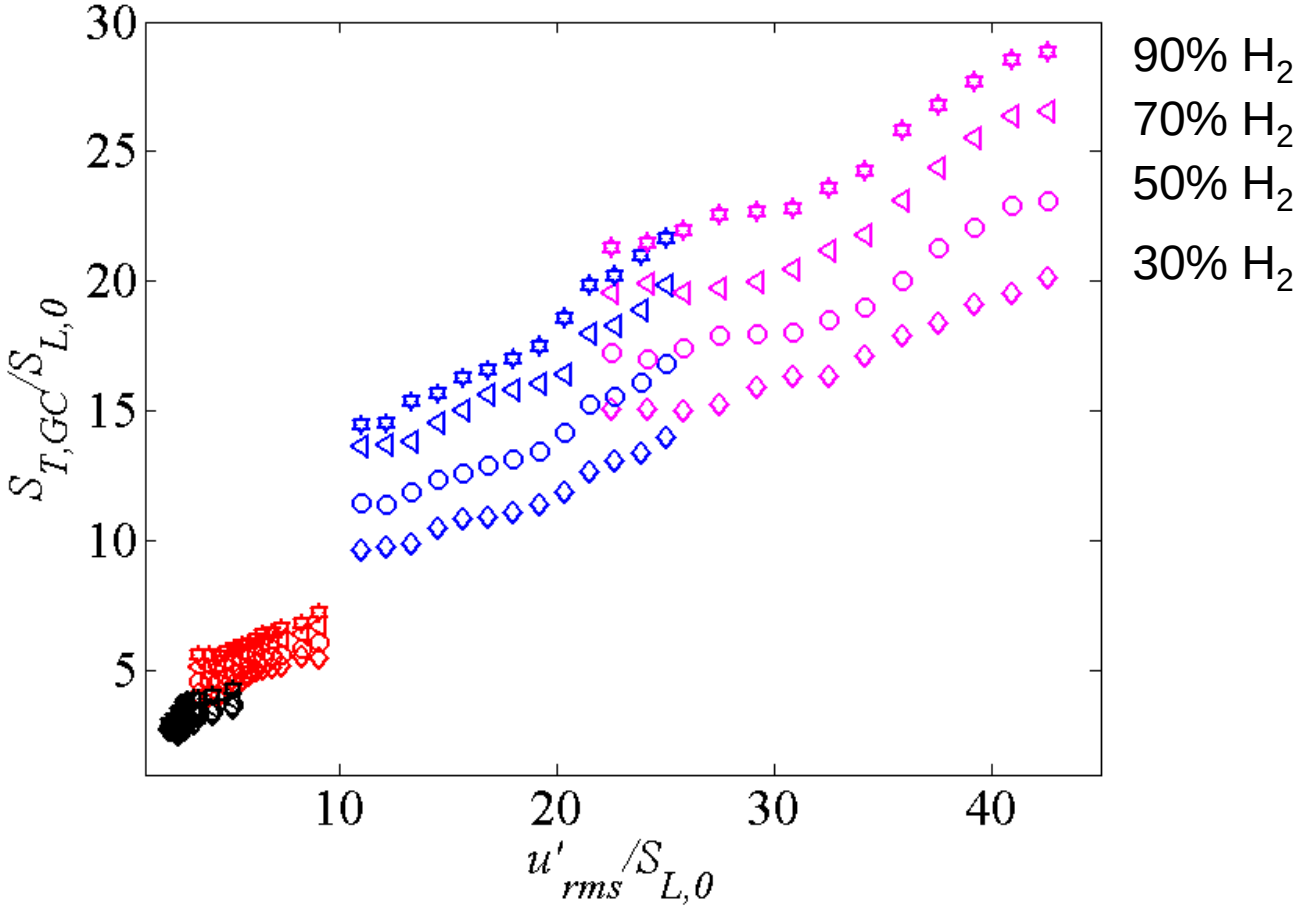
- Two Caveats:
  - We measured $S_{T,GC}$, scaling is really for $S_{T,LD}$
  - Measured $S_{T,GC}$ averages over variations on a spatially evolving turbulent flame brush

Normalization Results – 50 m/s

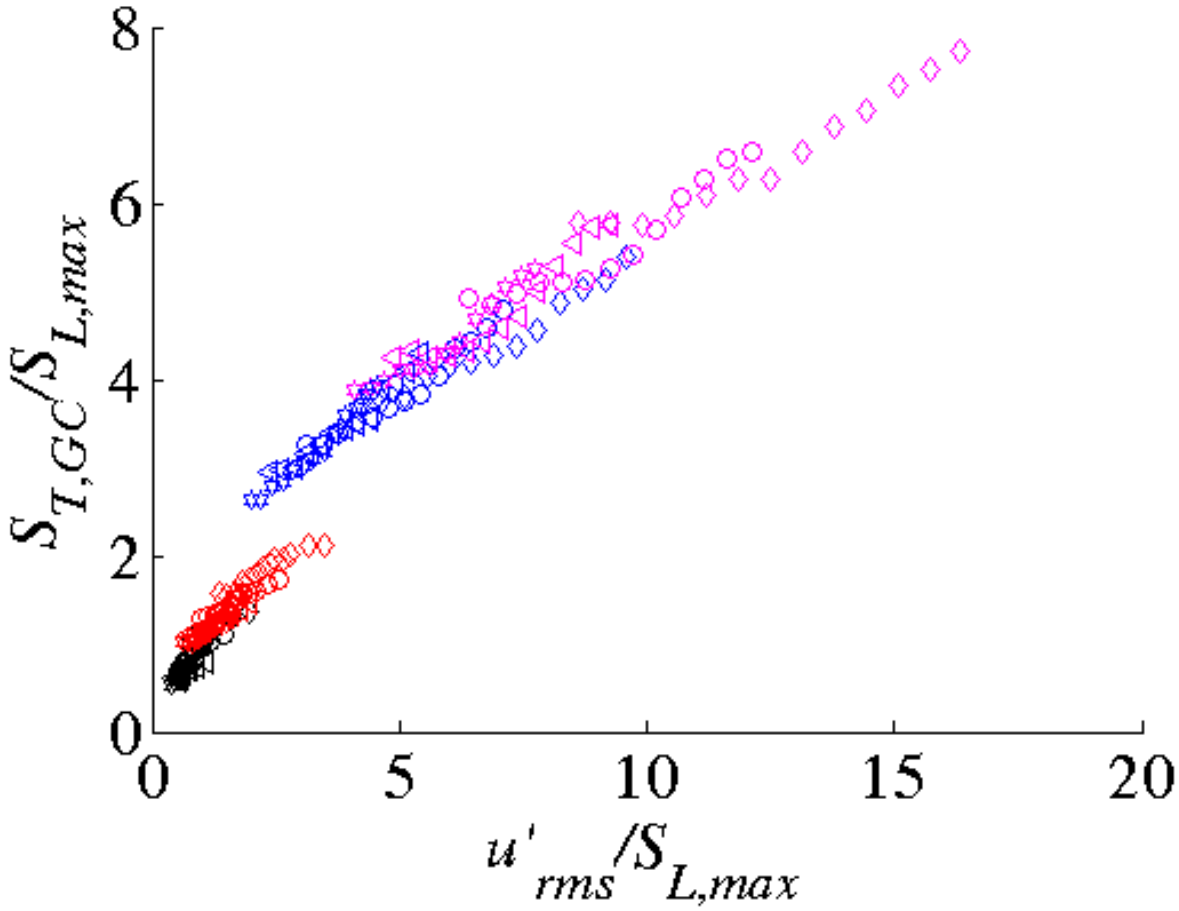


- Total variation from 90% H_2 to 30% H_2 drops from a factor of 1.5 to 1.1

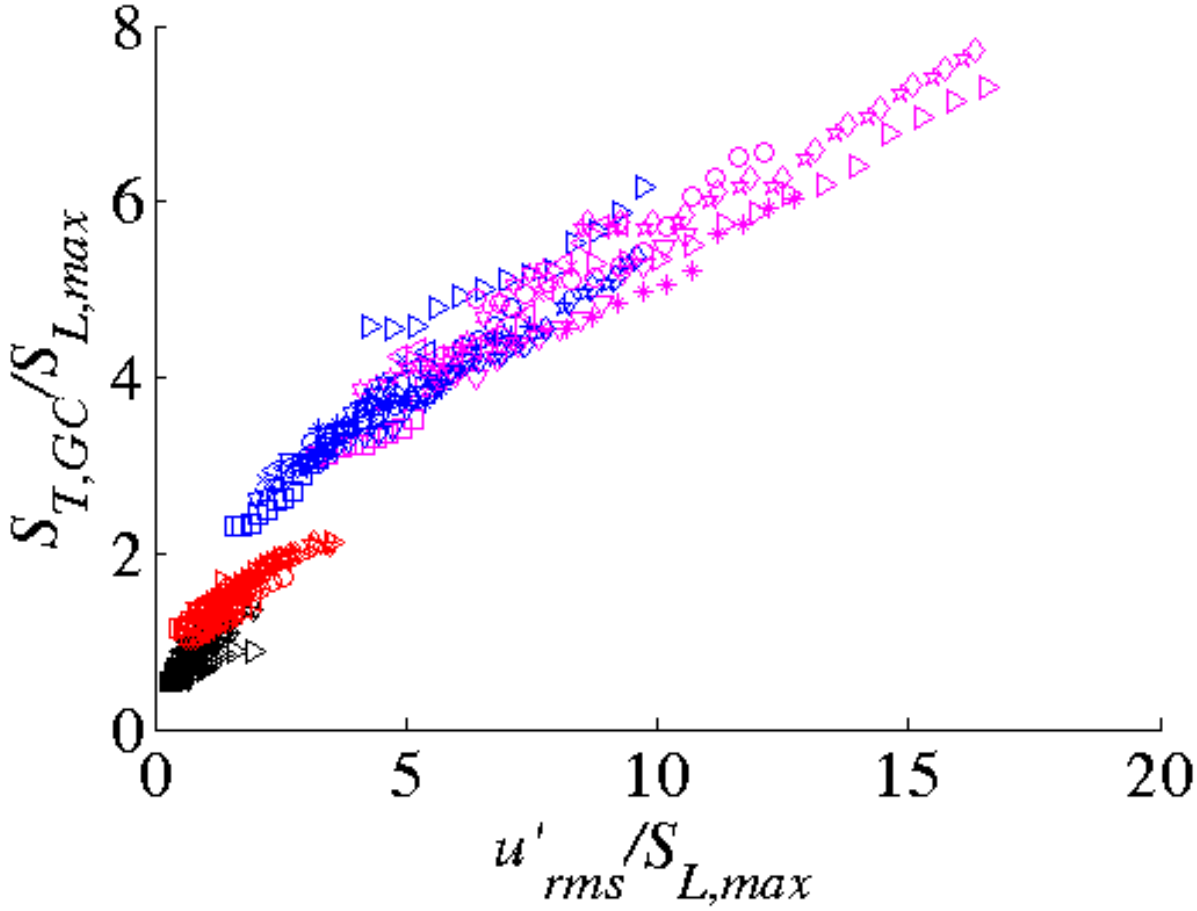
Normalization of H_2/CO Sweep Data – 20 mm



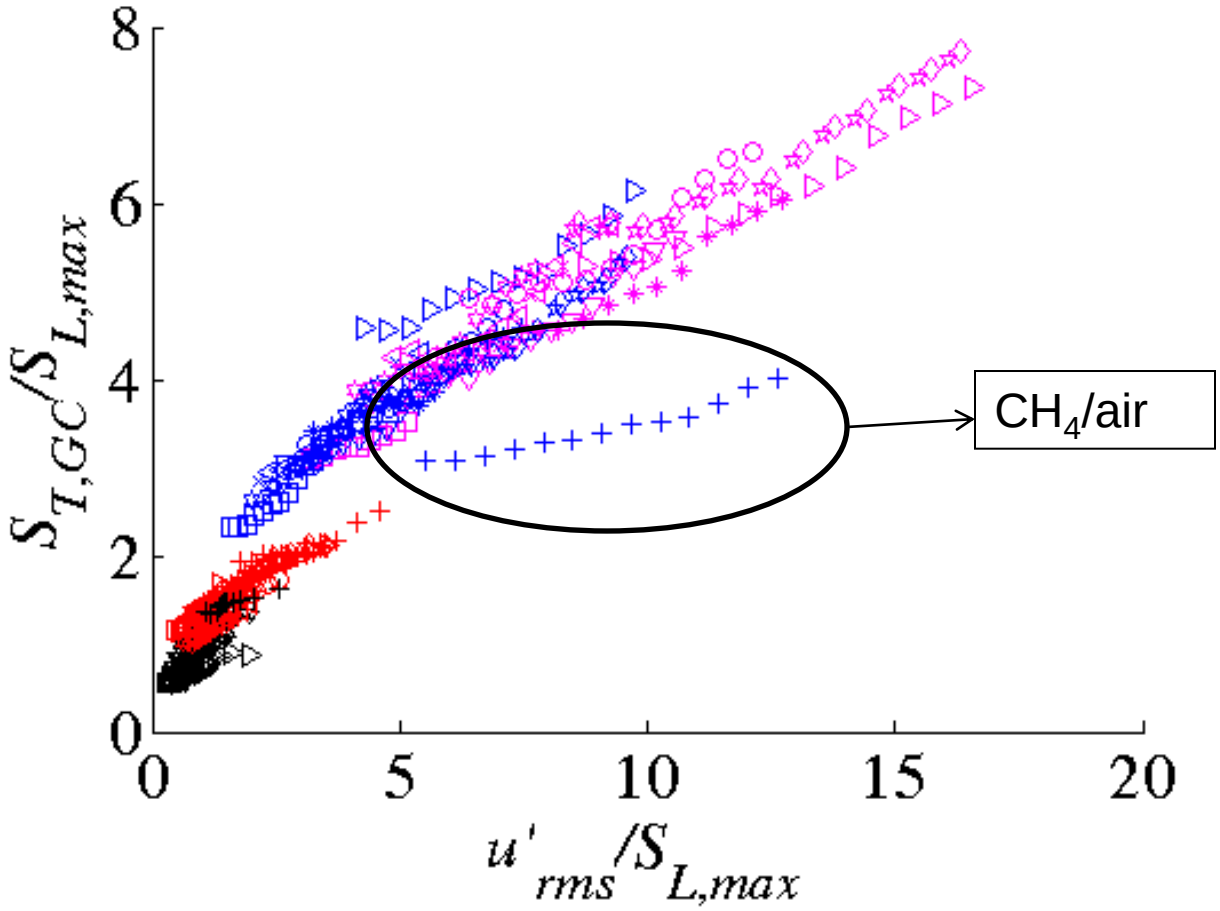
Normalization of H_2/CO Sweep Data – 20 mm



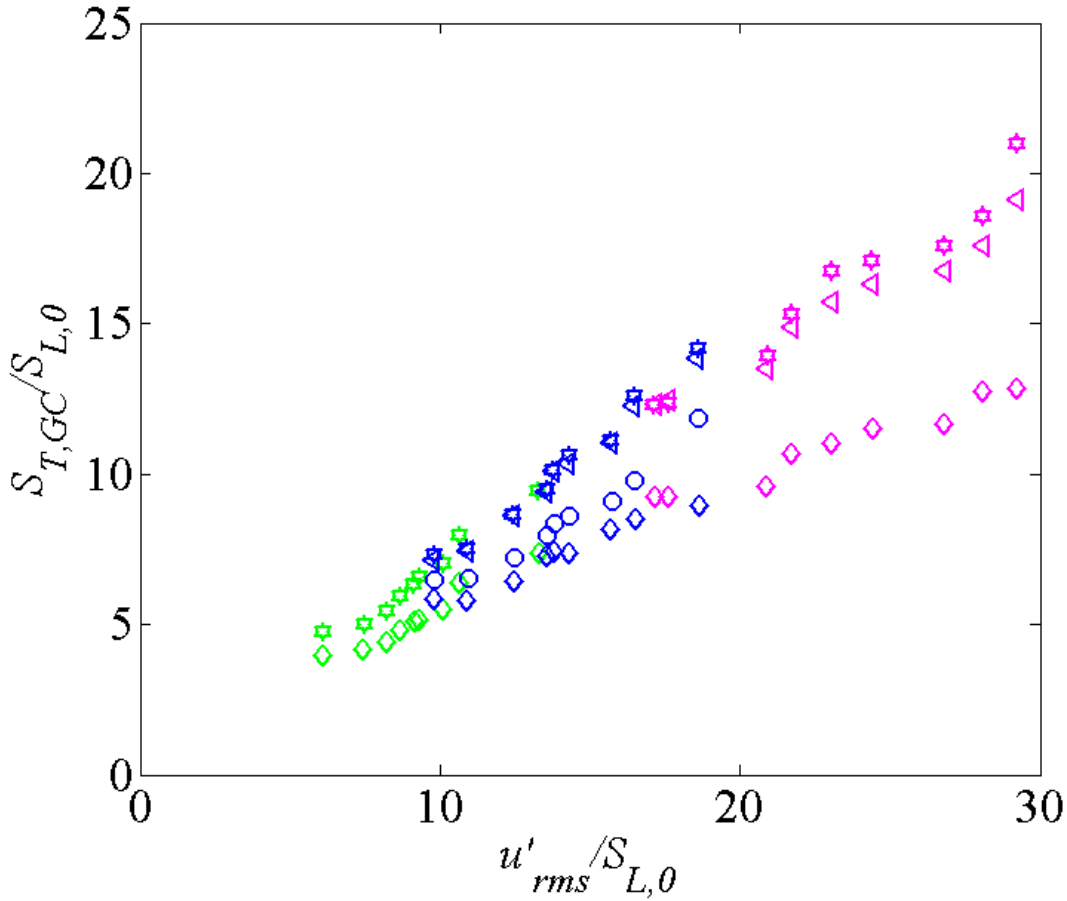
Normalization of Constant $S_{L,0}$ and Φ Sweep Data – 20 mm



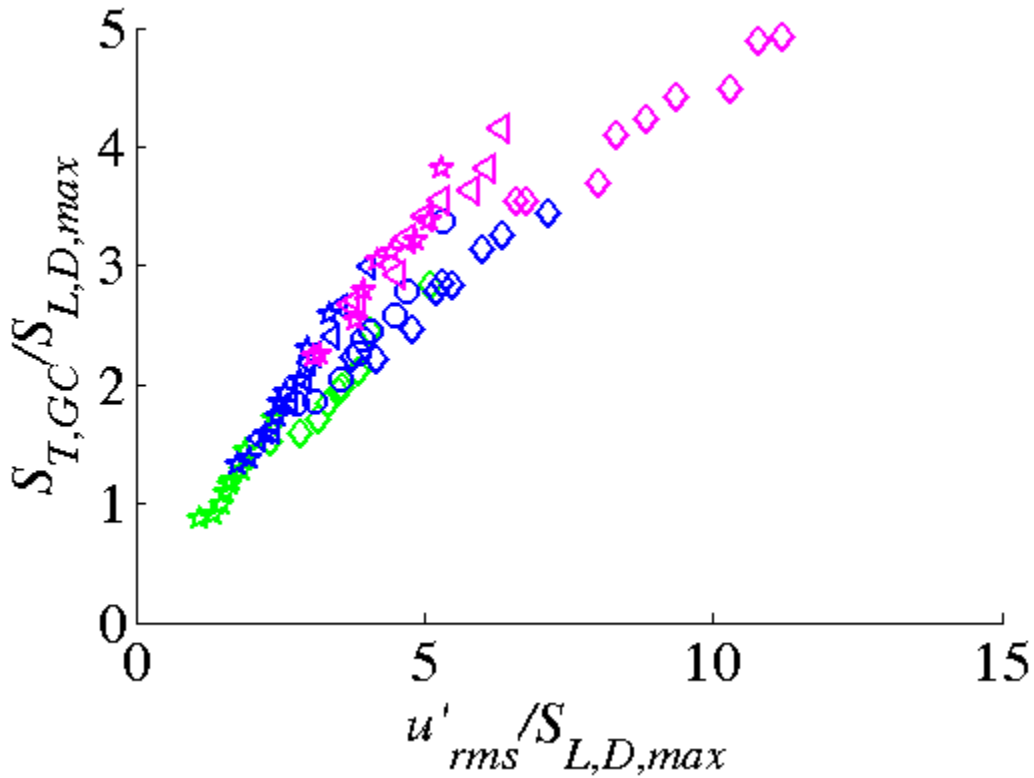
Normalization of H_2/CO and CH_4 data – 20 mm



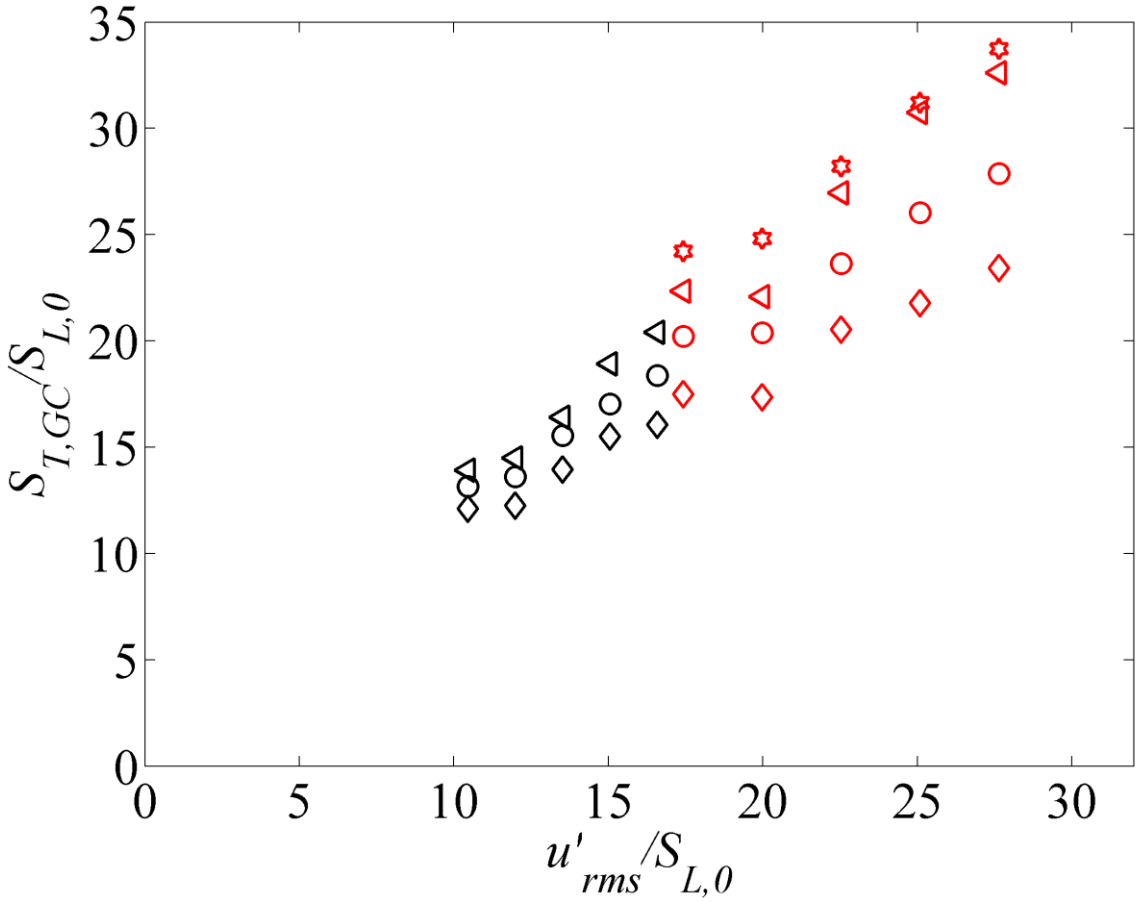
Normalization of Constant $S_{L,0}$ Data – 12 mm, 1atm



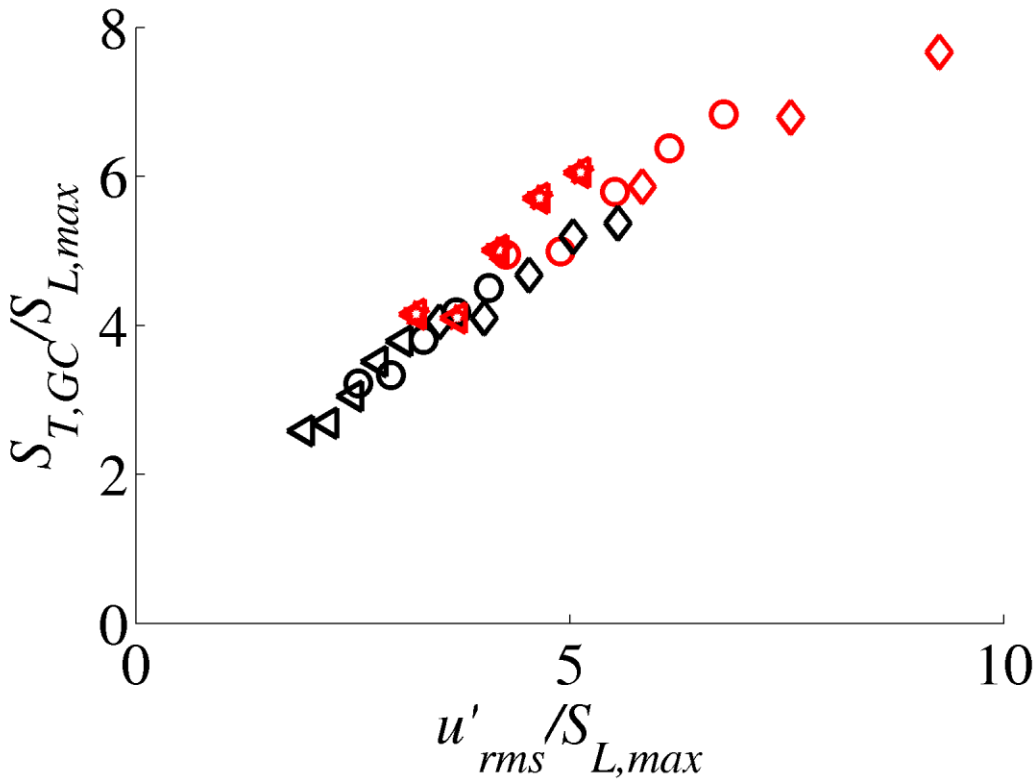
Normalization of Constant $S_{L,0}$ Data – 12 mm, 1atm



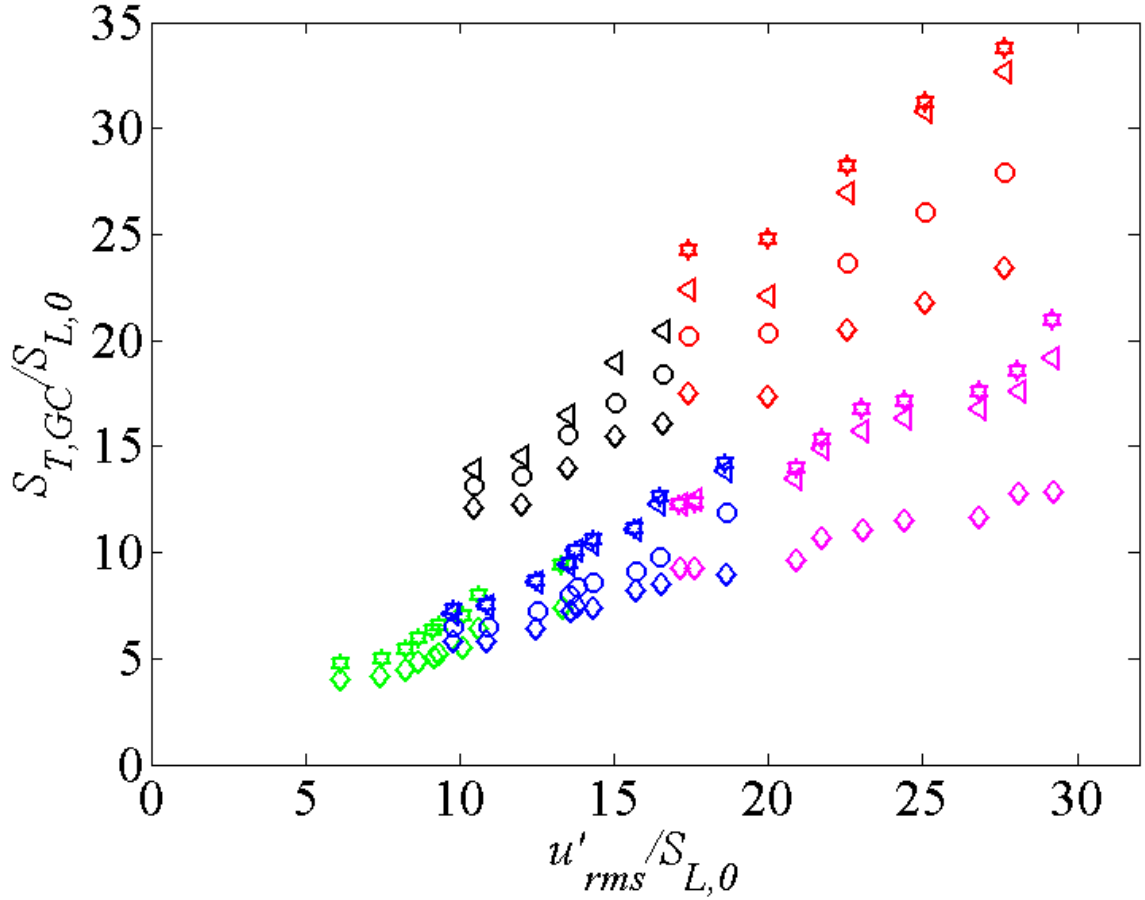
Normalization of Constant $S_{L,0}$ Data – 12 mm, 5atm



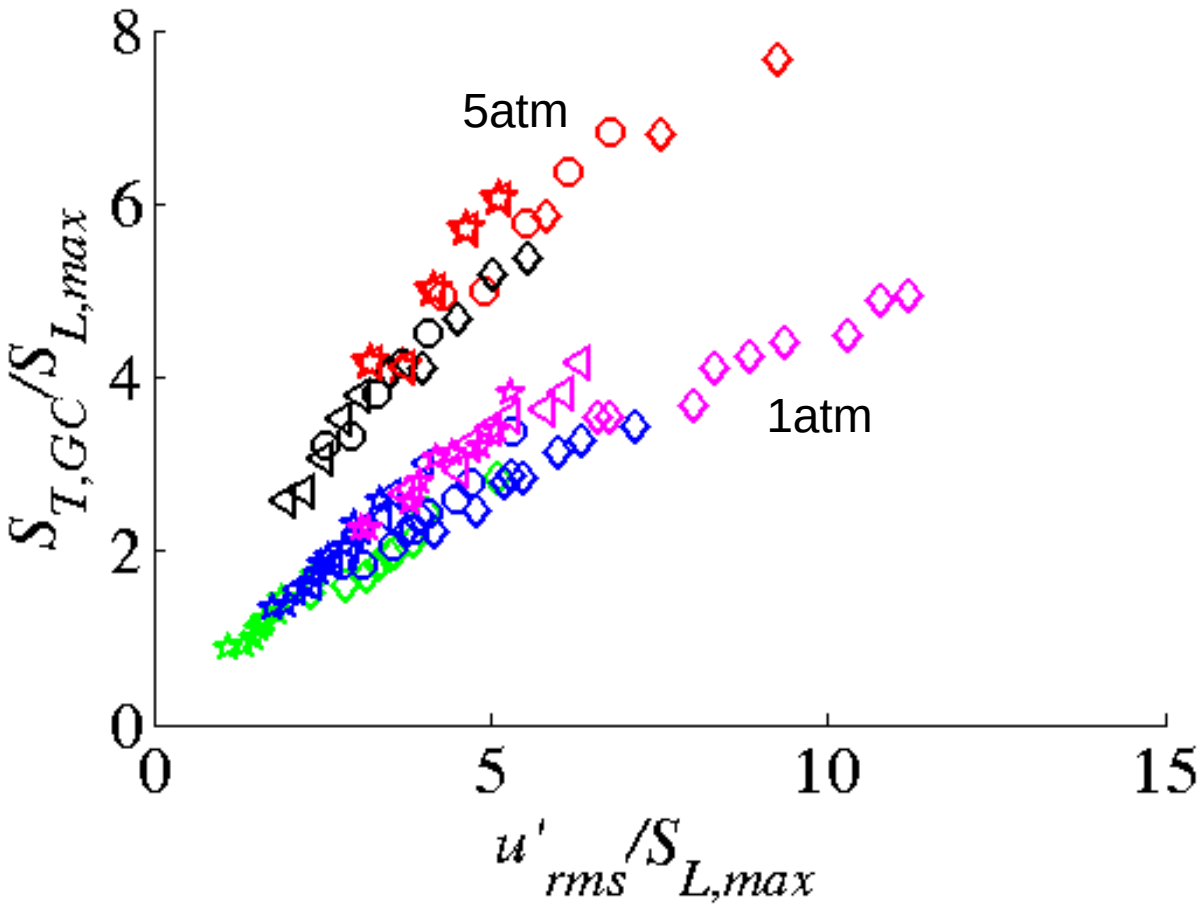
Normalization of Constant $S_{L,0}$ Data – 12 mm, 5 atm



Normalization of Constant $S_{L,0}$ Data – 12 mm, 1 and 5atm



Normalization of H_2/CO Sweep Data – 12 mm

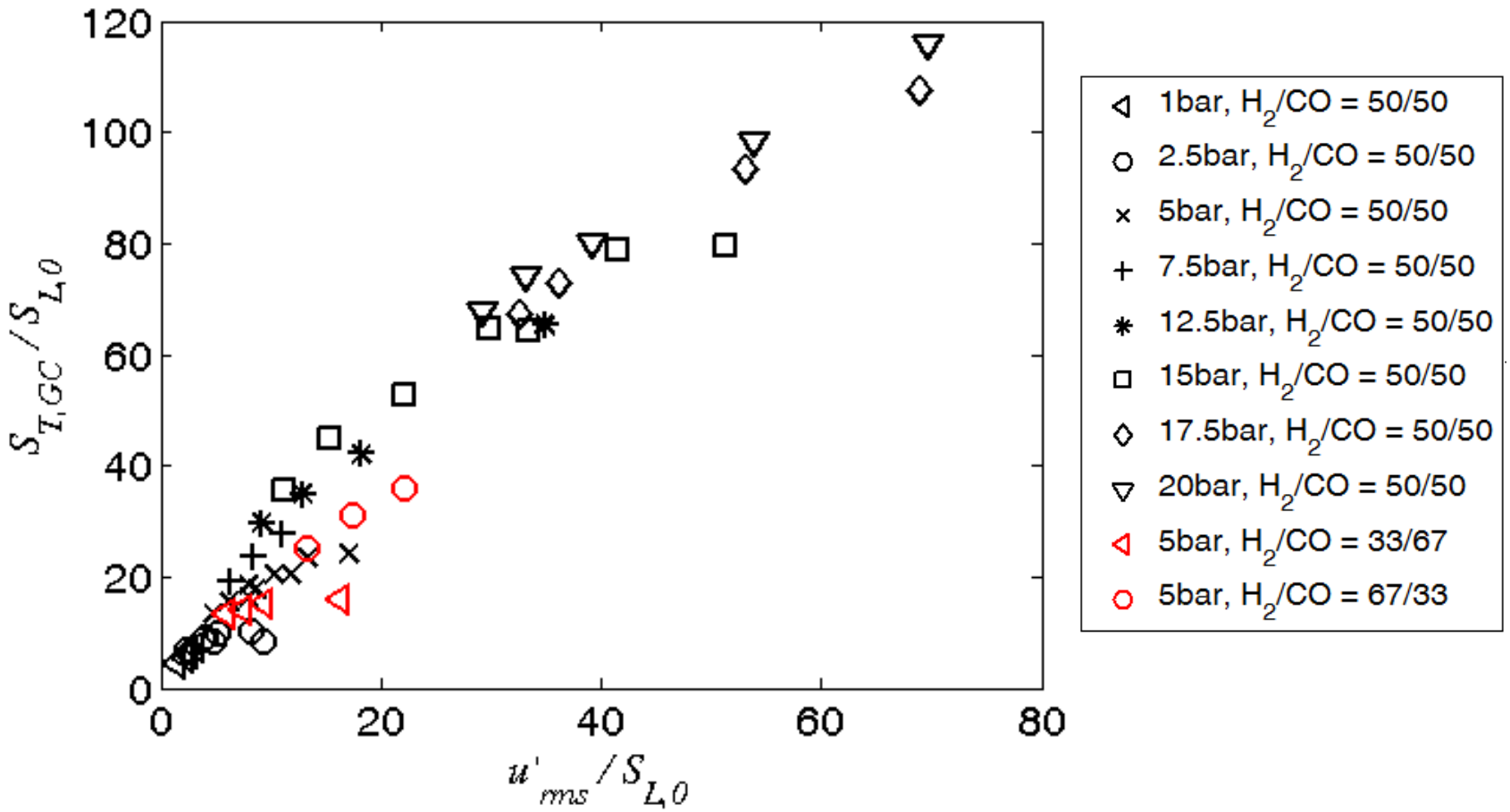


Other Datasets – Paul Scherrer Institute

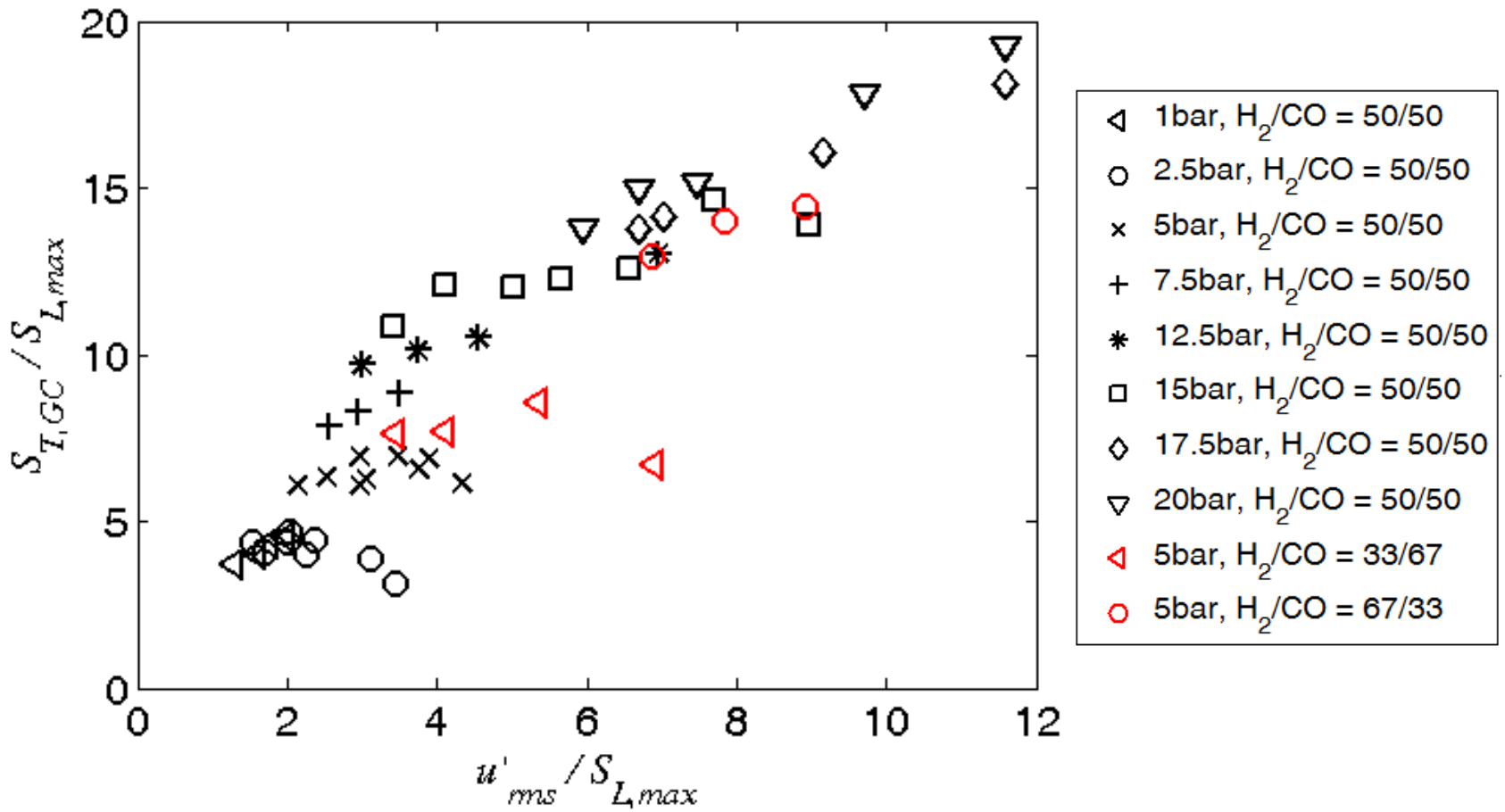
- $S_{T,GC}$ using Bunsen configuration
- Conditions for measurements
  - Pressure: 1-20atm
  - Temperature: 623 K
  - Fuel mixtures: H_2/CO = 33/67, 50/50, 67/33

S. Daniele; P. Jansohn; J. Mantzaras; K. Boulouchos, Proceedings of the Combustion Institute 33 (2) (2011) 2937-2944

$S_{L,0}$ normalized



$S_{L,max}$ normalized

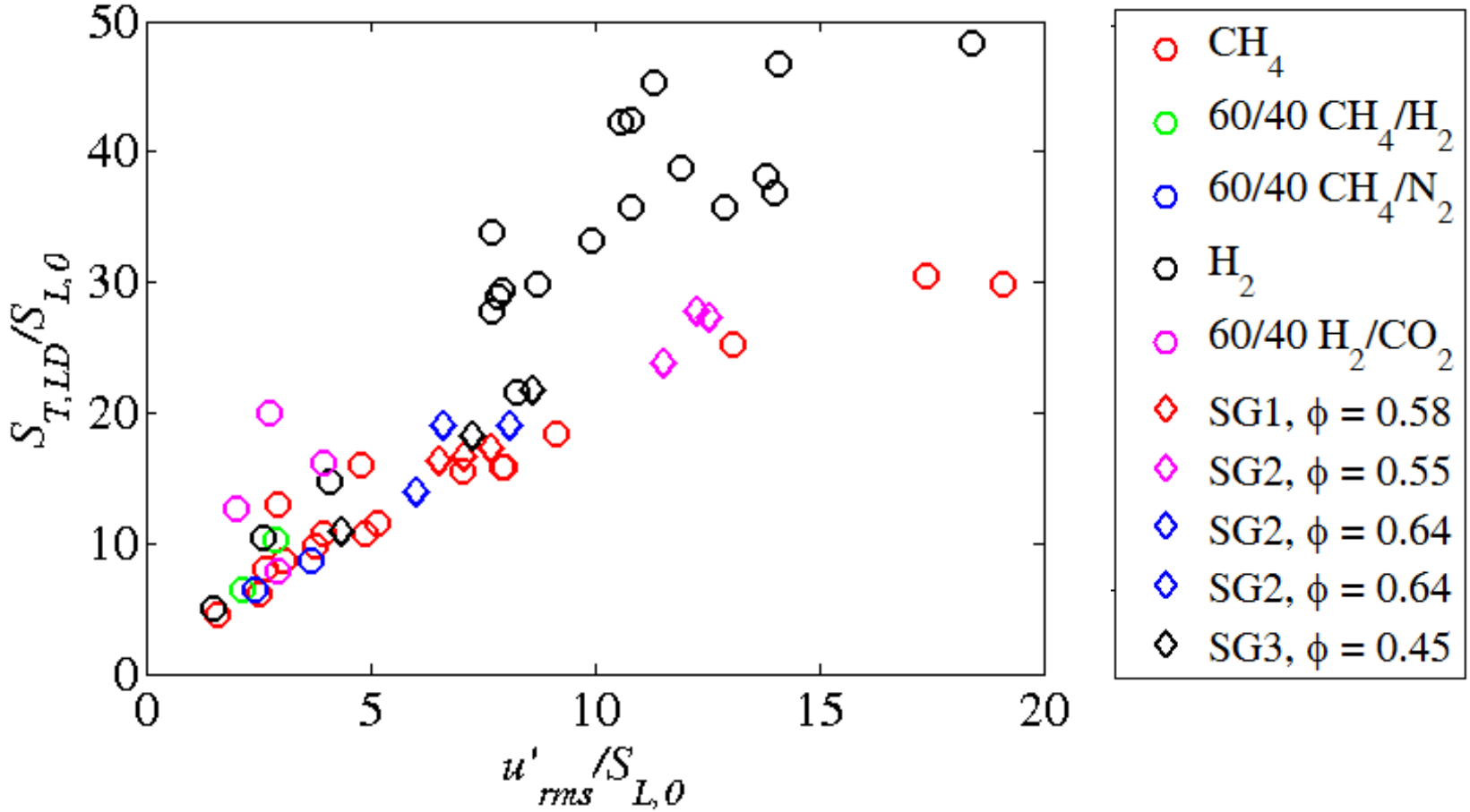


LBNL Database

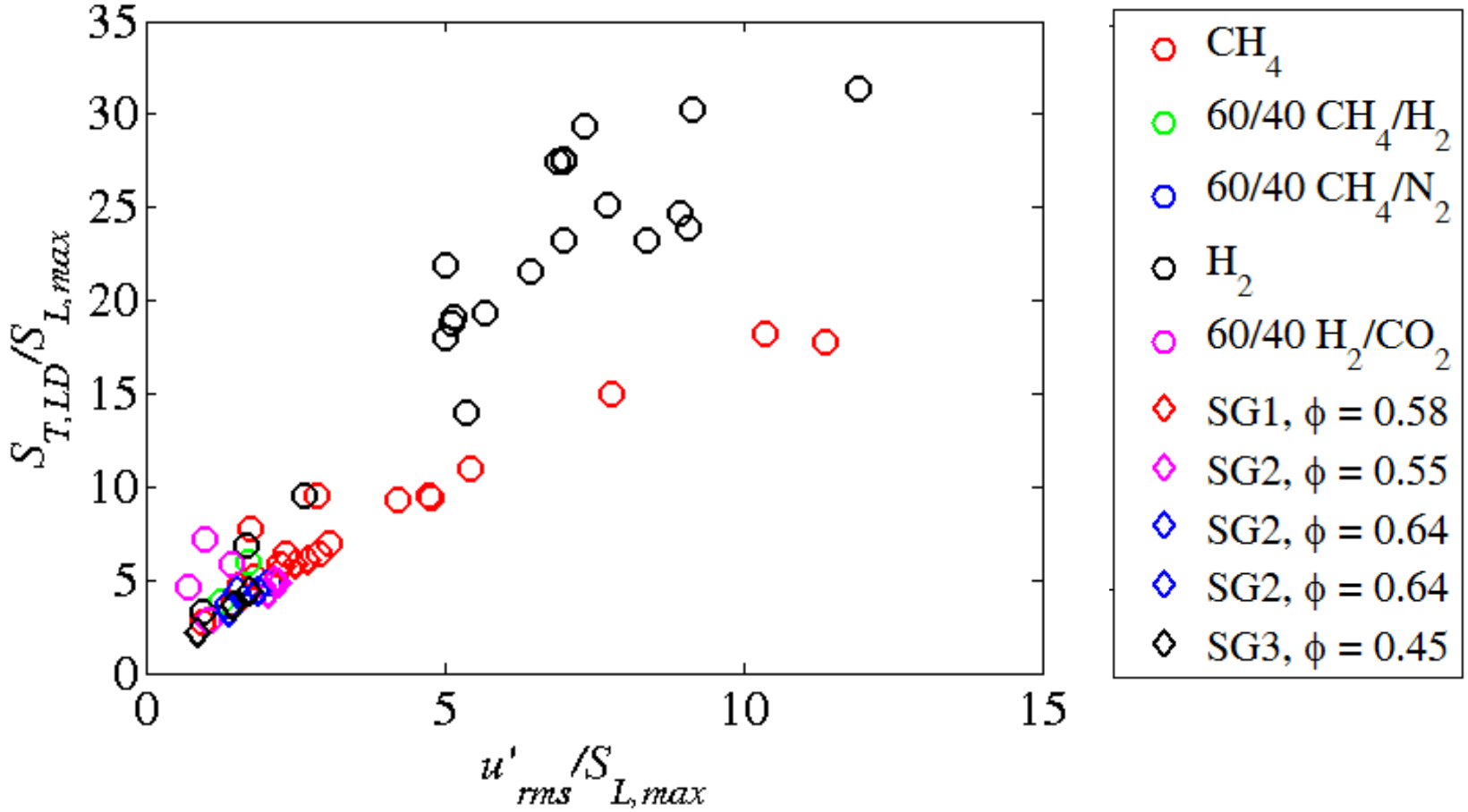
- $S_{T,LD}$ using low swirl injector (LSI) configuration
- Conditions for measurements
  - Pressure: 1atm
  - Temperature: 300 K
  - Fuel Mixtures: Various syngas blends

D. Littlejohn; R. K. Cheng, Proceedings of the Combustion Institute 31 (2) (2007) 3155-3162
D. Littlejohn; R. K. Cheng; D. R. Noble; T. Lieuwen, Journal of Engineering for Gas Turbines and Power 132 (1) (2010) 011502-8

$S_{L,0}$ normalized



$S_{L,\max}$ normalized

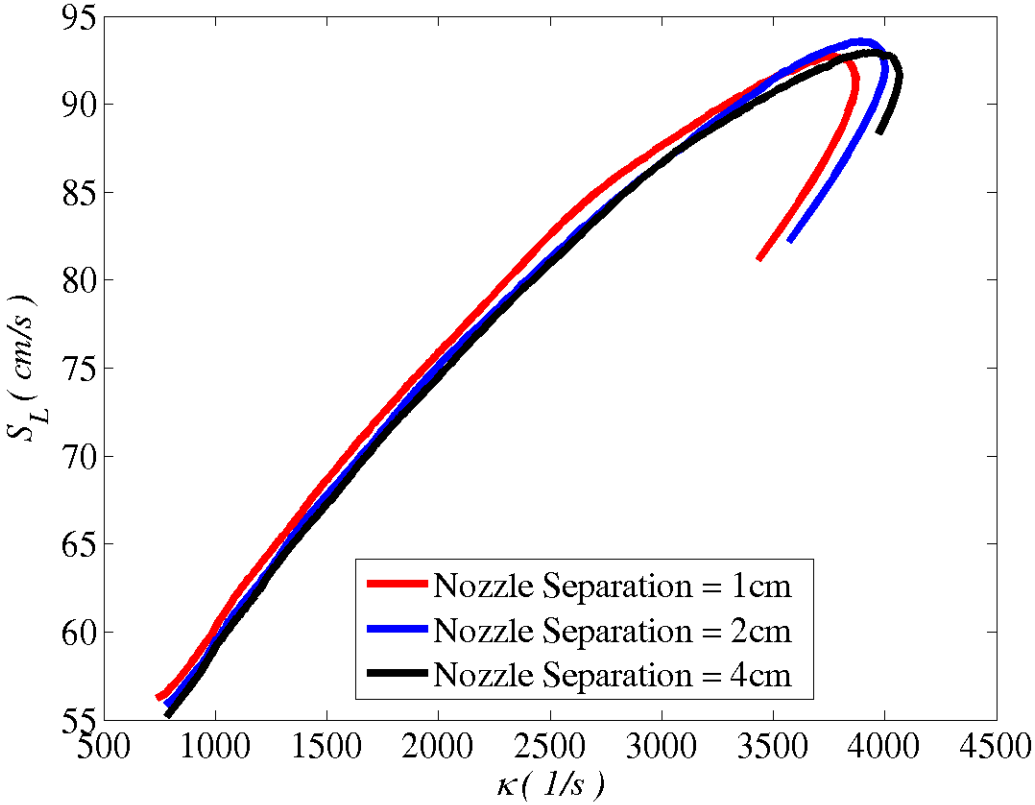


Discussion on $S_{L,max}$ characteristics

Comments on $S_{L,max}$ Dependencies

- Suggests that $S_{L,max}$ is the natural dynamical parameter for scaling data
- $S_{L,max}$ is not an intrinsic property of the mixture
  - Burning velocity definition
  - Hydrodynamic strain vs. curvature induced flame stretch
  - Flow strain profile through flame; e.g.;
    - Nozzle separation distance in OPPDIFF
    - Potential flow vs. plug flow nozzle exit velocity profile
  - Non quasi-steady chemistry for unsteady problems

Hydrodynamic Strain Profile Through Flame



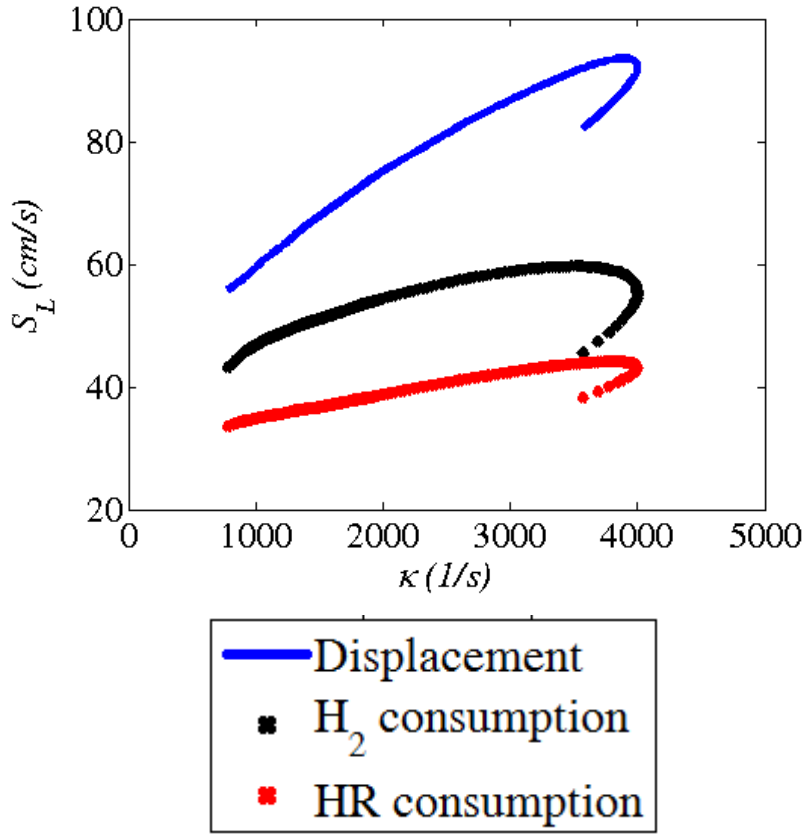
- H_2/CO = 30/70, T_u = 298 K, P = 1 atm, $S_{L,0}$ = 34 cm/s
- Nozzle separation → alters strain rate profile through the flame

Burning Velocity Definitions

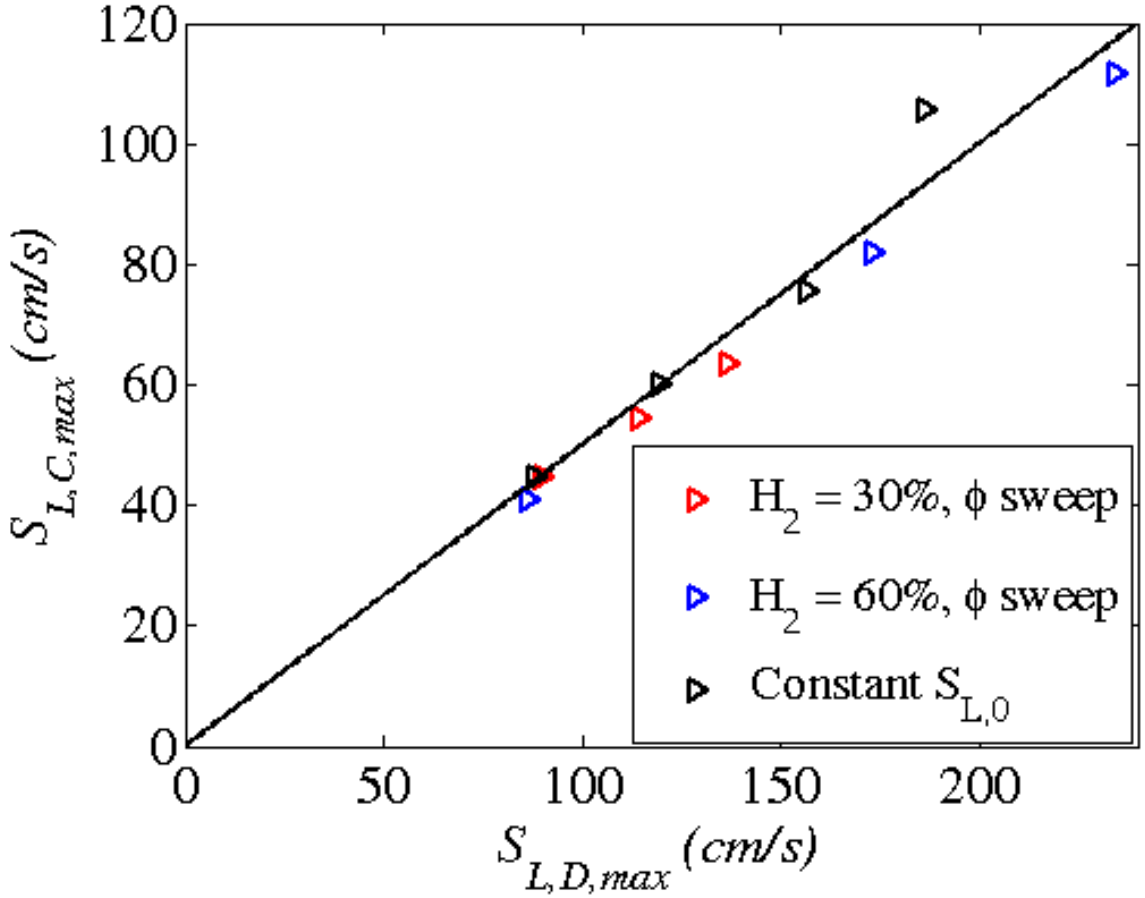
- Can define both consumption and displacement speeds
  - Values can be quite different for highly stretched flames

$$S_{L,C,mass} = \frac{\int_{-\infty}^{\infty} \dot{w}_i dx}{\rho_u \left(Y_{i,\infty} - Y_{i,-\infty} \right)}$$

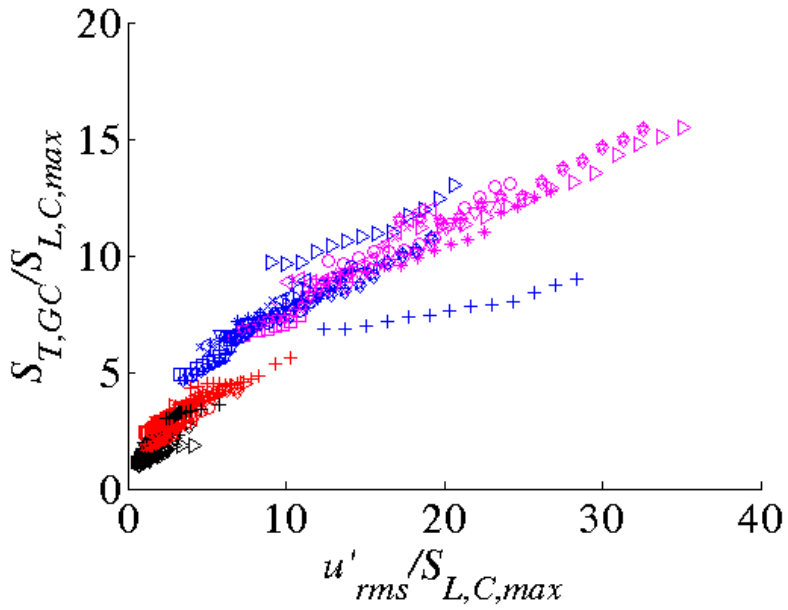
$$S_{L,C,thermal} = \frac{\int_{-\infty}^{\infty} \dot{q} dx}{\rho_u \left(h_{sens,\infty} - h_{sens,-\infty} \right)}$$



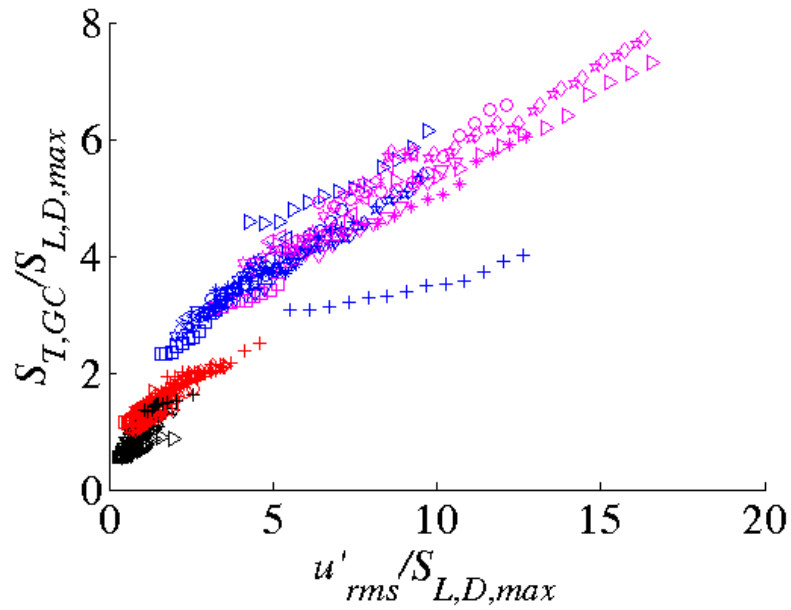
Consumption vs. Displacement speed



Consumption Speed Normalization

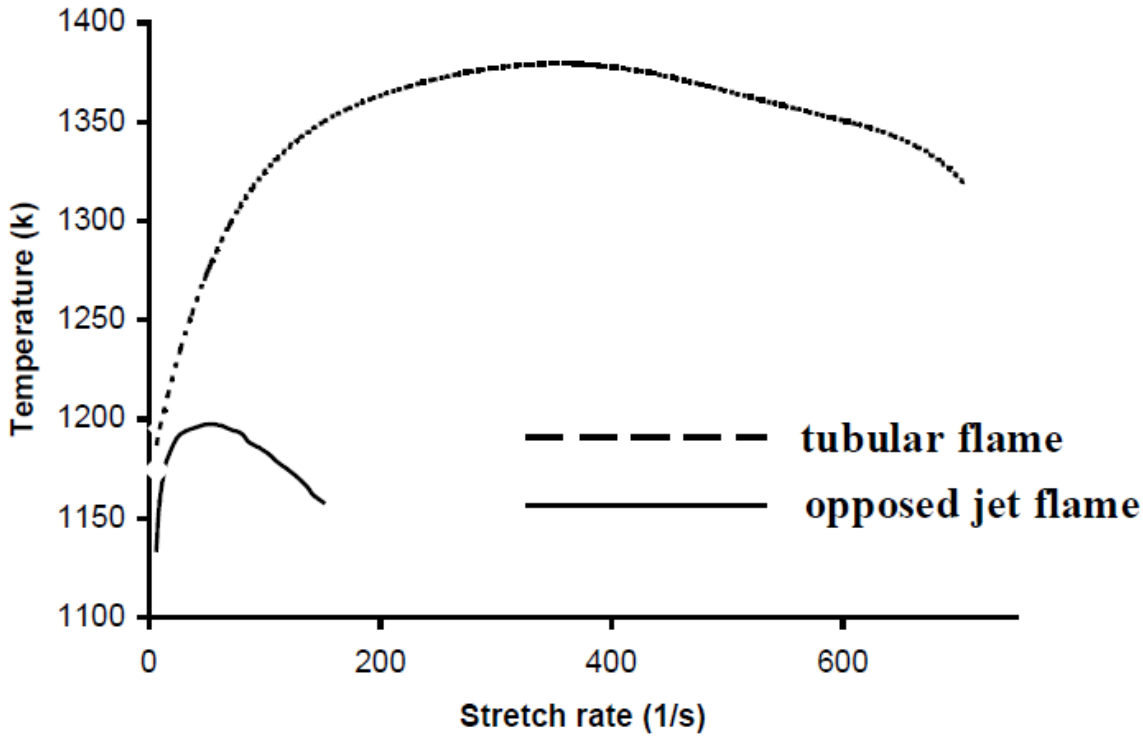


Consumption Speed Scaling



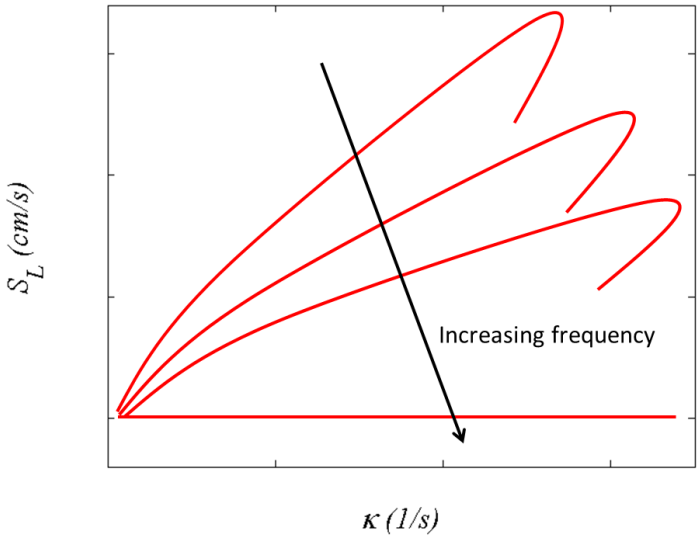
Displacement Speed Scaling

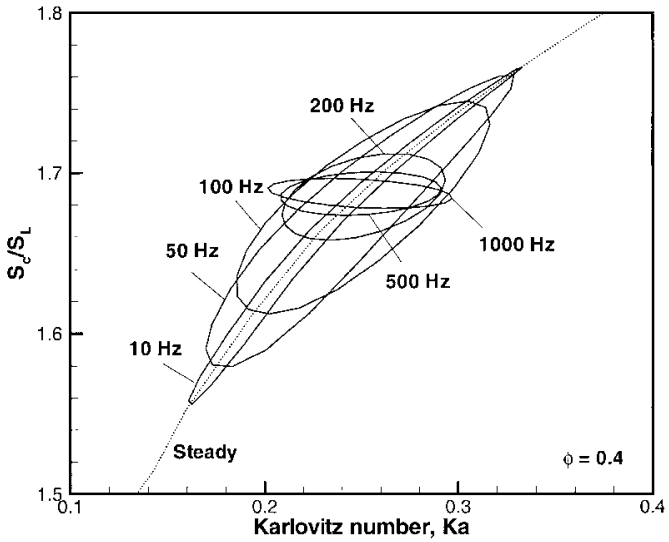
Hydrodynamic vs. Curvature Induced Stretch



- H_2/air, $\Phi = 0.75$, $T_u = 298$ K

Unsteady Strain Rate Effects





(a)

- Unsteady strain → lag in flame response
  - Effective Markstein number drops with increasing fluctuation frequency
- Evaluating chemical time parameter, in addition to $S_{L,max}$ as second parameter for correlating data

H. G. Im; J. H. Chen, Proceedings of the Combustion Institute 28 (2) (2000) 1833-1840

Key Accomplishments

- $S_{T,GC}$ data obtained at variety of conditions:
  - D = 12 and 20 mm
  - p = 1 and 5 atm
  - T_u = 300-600 K
  - U_0 = 4-50 m/s
  - H_2/CO ratios = 30/70-90/10
  - Φ = 0.4-0.8
  - $u'/S_{L,0}$ = 0-100

- Data clearly shows that "fuel effects" persist at high $u'/S_{L,0}$
  - $S_{T,GC}$ increases with H_2 content in fuel, even at $u'/S_{L,0}$ ~ 50
  - Similar effects seen for smaller burner diameters and preheated conditions
  - Implication: $S_{T,GC}$ cannot be parameterized by $u'/S_{L,0}$ and $S_{L,0}$ alone

- Results consistent with preferential diffusion and non-unity Lewis number mechanisms for $S_{T,GC}$ variation (Driscoll 2008)

- Developed a physics-based model on derived from leading points theory
  - Suggests that $S_{L,max}$ and not $S_{L,0}$ is the appropriate normalizing parameter
  - Investigate parametric dependency of $S_{L,max}$
  - Development of numerical tool to calculate curvature induced flame stretch sensitivity using COMSOL

Driscoll, J.F., Progress in Energy and Combustion Science, 2008

UNSTEADY COMBUSTOR PHYSICS

Tim Lieuwen

Cambridge Press, to appear in 2012

- 530 pages, 12 chapters, with exercises

1. Overview and Basic Equations

Section I: Flow Disturbances in Combustors
2. Decomposition and Evolution of Disturbances
3. Hydrodynamic Flow Stability I: Introduction
4. Hydrodynamic Flow Stability II: Common Combustor Flow Fields
5. Acoustic Wave Propagation I: Basic Concepts
6. Acoustic Wave Propagation II: Heat Release, Complex Geometry, and Mean Flow Effects

Section II: Reacting Flow Dynamics
7.Flame-Flow Interactions
8. Ignition
9. Internal Flame Processes

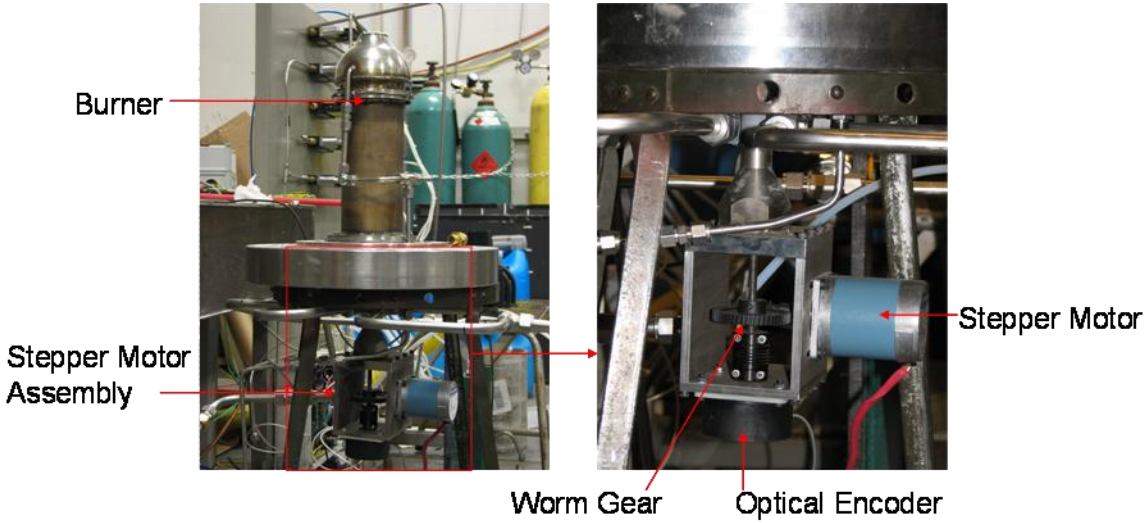
Section III: Transient and Time-Stationary Combustor Phenomenon
10. Flame Stabilization, Flashback, and Blowoff
11. Forced Response I - Flamelet Dynamics
12. Force Response II- Heat Release Dynamics

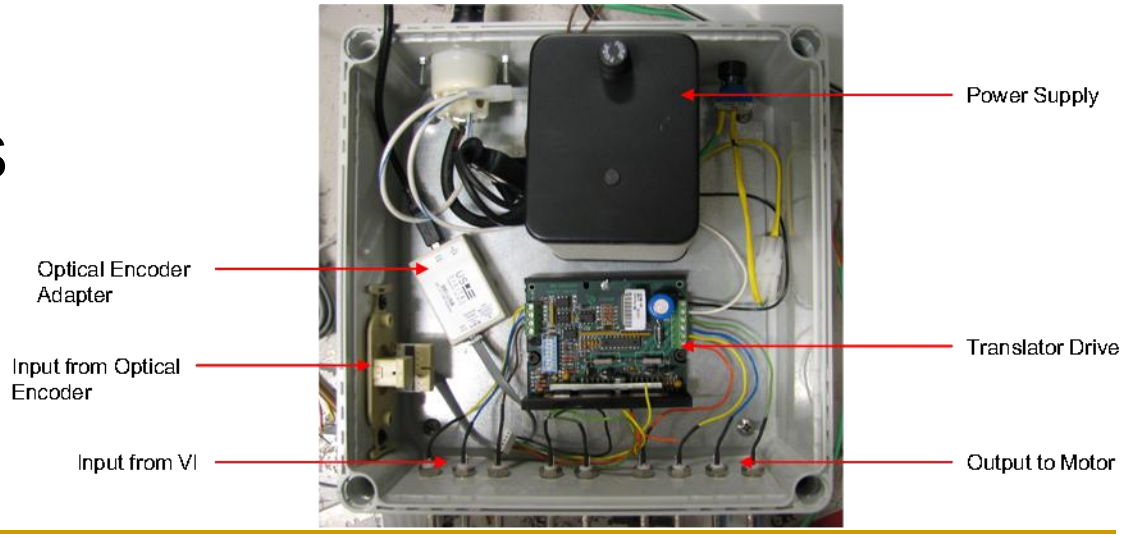
Questions?

Extra Slides

Turbulence Generator – Remote Operation

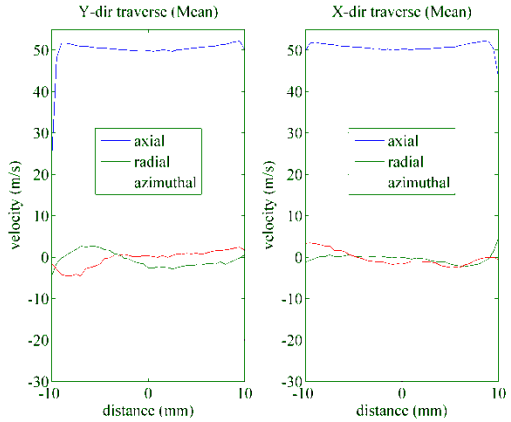
- Operates remotely
- Resolution of ±0.1°
- Repeatable measurements



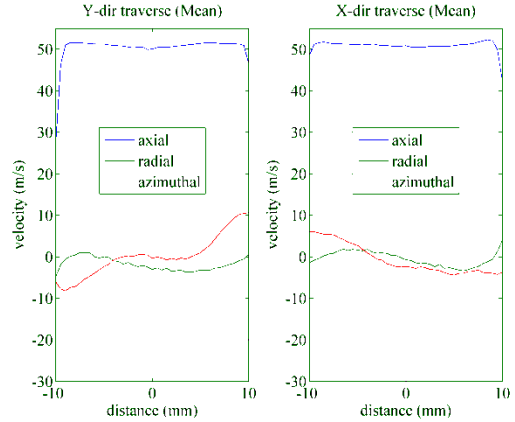


Velocity Characterization – Mean Profile Evolution with Blockage Ratio

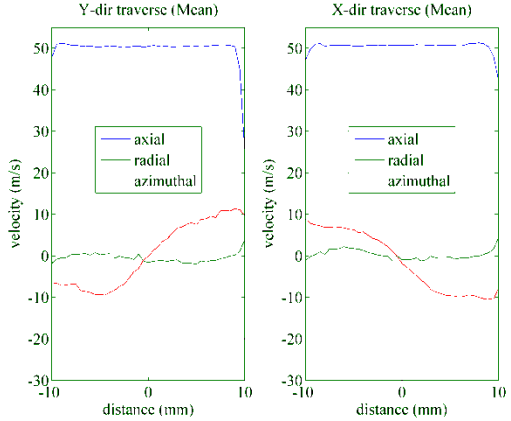
U = 50 m/s, BR = 69%



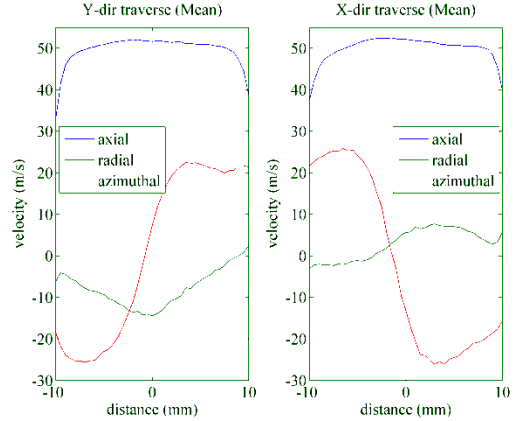
U = 50 m/s, BR = 77%



U = 50 m/s, BR = 89%

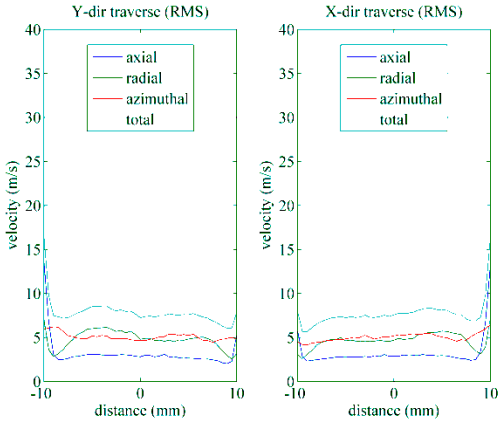


U = 50 m/s, BR = 97%

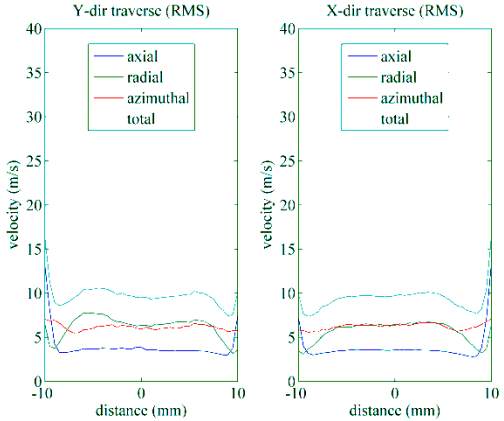


Velocity Characterization – RMS Profile Evolution with Blockage Ratio

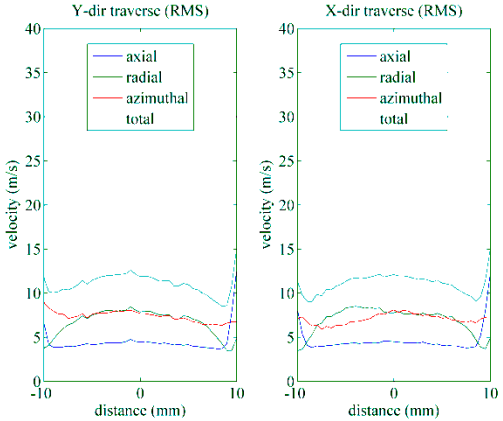
U = 50 m/s, BR = 69%



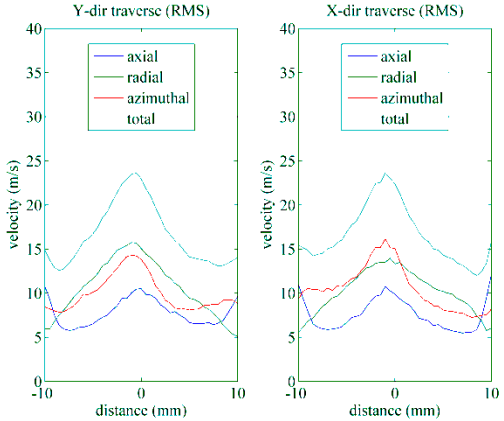
U = 50 m/s, BR = 77%



U = 50 m/s, BR = 89%



U = 50 m/s, BR = 97%



Integral Length/Time Scales

- Determined autocorrelation from LDV data
  - Special techniques required because data not evenly sampled in time
    - Algorithm based on Mayo (1974) and Tummers (1996)

Algorithm:

$$\rho(k\Delta\tau) = \frac{\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} u_i u_j (k\Delta\tau)}{\sqrt{\sum_{i=1}^{N-1} u_i^2 (k\Delta\tau) \sum_{j=i+1}^{N} u_j^2 (k\Delta\tau)}} \quad \text{for: } k = 0,1,\ldots,M-1$$

$$\text{where: } \left(k-\tfrac{1}{2}\right)\Delta\tau < t_i - t_j < \left(k+\tfrac{1}{2}\right)\Delta\tau$$

$$M-1 = \frac{\tau_{\max}}{\Delta\tau}$$

$\tau_{\max}$: maximum lag time

$\Delta\tau$: slot width

Mayo Jr, W.T. A Discussion of Limitations and Extentions of Power Spectrum Estimation with Burst-Counter LDV Systems. in International Workshop on Laser Velocimetry. 1974. West Lafayette, Indiana, Purdue University.

Tummers, M.J., Passchier, Measurement Science and Technology, 1996. ***7****: p. 1541-1546****.***

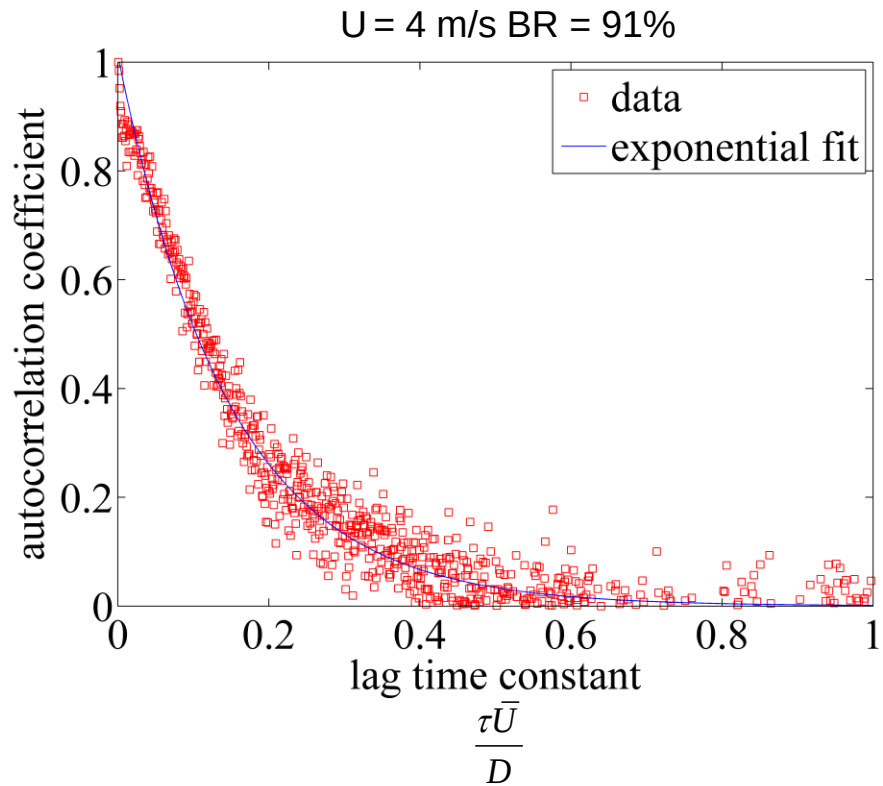
Integral Time Scales – Typical Result

- Data fit to exponential equation and integrated to determine τ_{int}

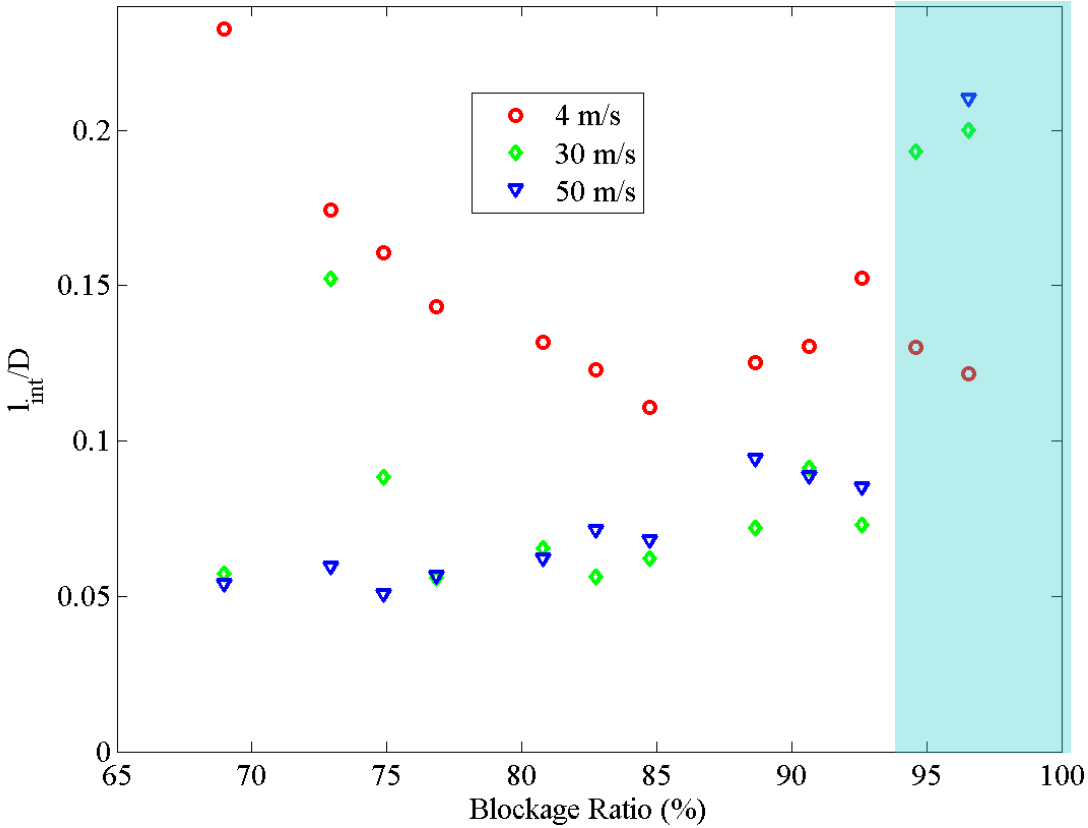
$$C(\tau) = ae^{-b\tau} + (1-a)e^{-c\tau}$$

$$\tau_{\text{int}} = \frac{a}{b} + \frac{1-a}{c}$$

$$l_{\text{int}} = U\tau_{\text{int}}$$



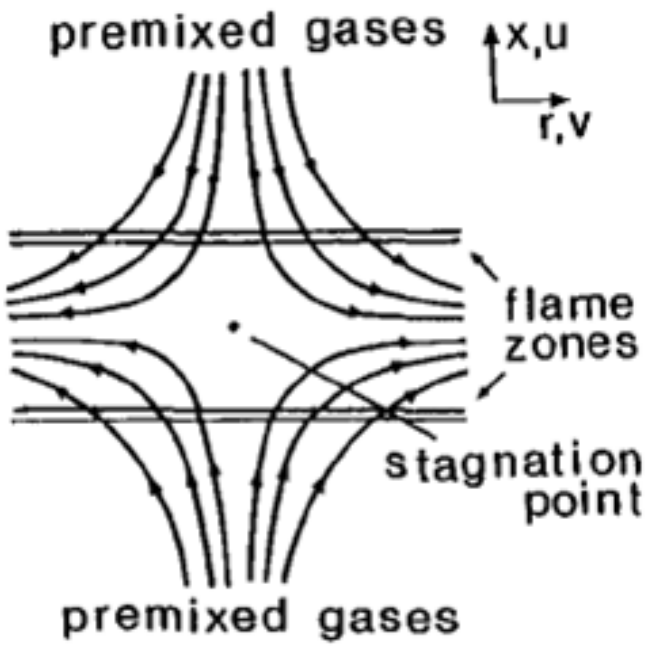
Integral Length/Time Scales Results

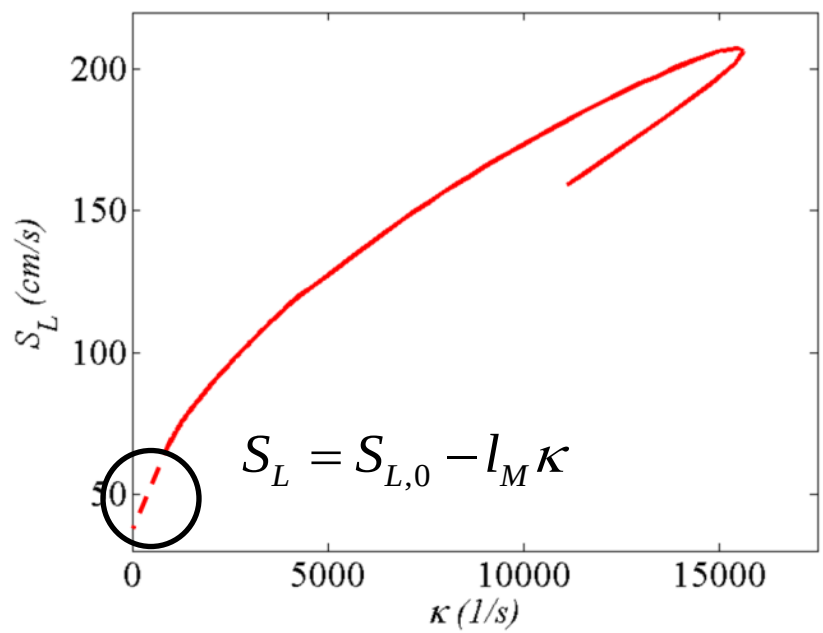


High swirl regime

- Data shows l_{int}/D ~ 0.06 - 0.15
  - l_{int} doesn't scale with slit width of turbulence generating plates

Stretch Sensitivity





- CHEMKIN-OPPDIFF module
  - Symmetric opposed jet configuration
  - Detailed kinetics and multicomponent transport
    - H_2/CO: Davis
    - CH_4: GRI 3.0

G. P. Smith; D. M. Golden; M. Frenklach; N. W. Moriarty; B. Eiteneer; M. Goldenberg; C. T. Bowman; R. K. Hanson; S. Song; W. C. Gardiner Jr; V. V. Lissianski; Z. Qin GRI-Mech 3.0. http://www.me.berkeley.edu/gri_mech/
S. G. Davis; A. V. Joshi; H. Wang; F. Egolfopoulos, Proceedings of the Combustion Institute 30 (1) (2005) 1283-1292