UTSR: H_2 COMBUSTION FOR GAS TURBINES

BURNING VELOCITY AND EMISSIONS OF HYDROGEN BLENDED FUELS

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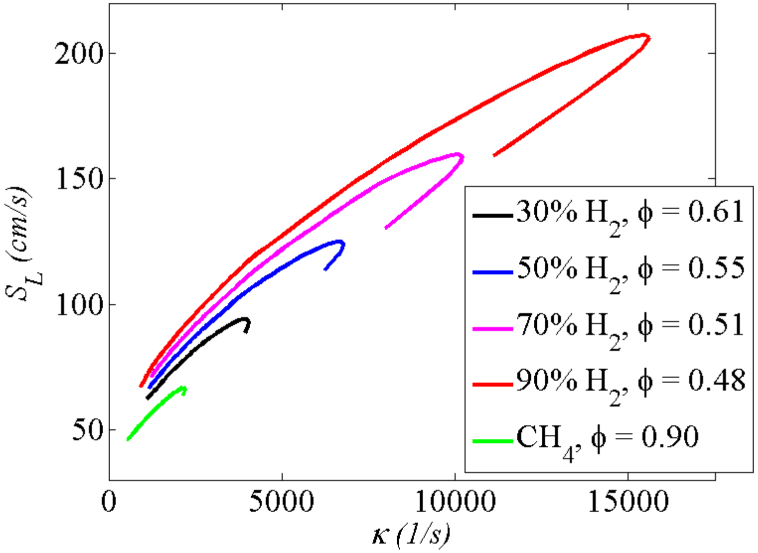
BACKGROUND

- Turbulent flame speed, S_T, is a key combustion parameter that impacts the performance of combustion systems
  - Flame length – emissions, combustion instabilities
  - Flame stability, particularly flashback

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

- H_2 has fundamentally different propagation properties as compared to hydrocarbon fuels – at least 4x increment in laminar propagation speed at a constant T_{ad}.

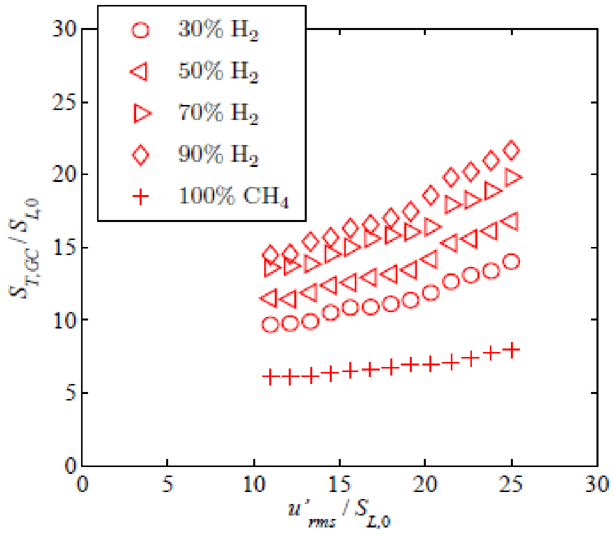


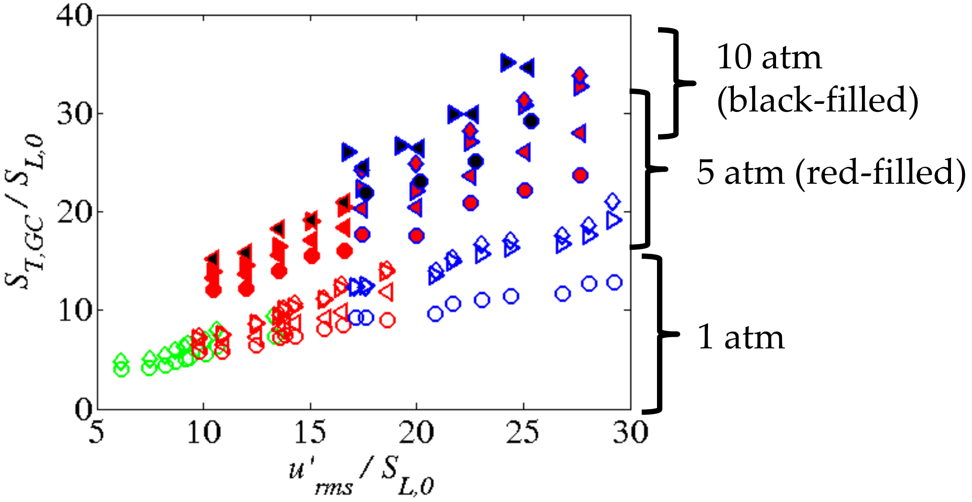
MOTIVATION

Traditional turbulent flame speed correlation

$$S_T = S_{L,0} f\left(u'/S_{L,0}\right)$$

Data shows that S_T varies with fuel/pressure/preheat, even at constant $S_{L,0}$ and u'





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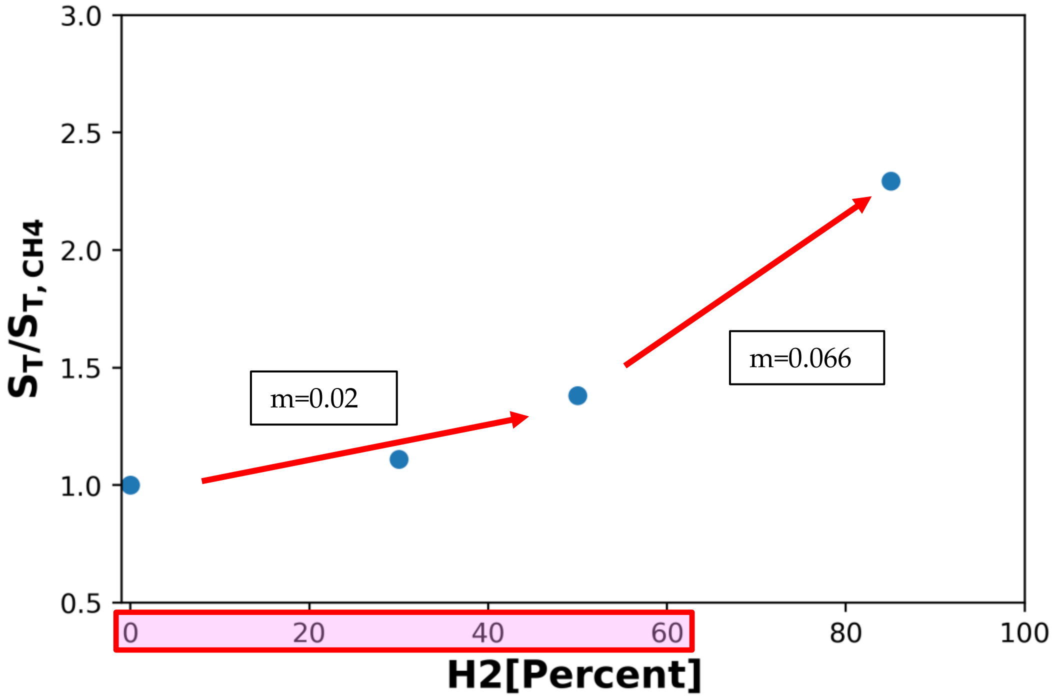
MOTIVATION
EFFECT OF H_2 ADDITION AT CONSTANT T_{ad}

Data conditioned on : P=2 bar, T=300K, U0 ~30 m/s, **T_{ad} = 2150±20K, BR=69%**



$$m = \frac{\partial S_T}{\partial H_2}$$

Significant increase seen above 60% H_2

EXPERIMENTAL FACILITY AND DATABASE

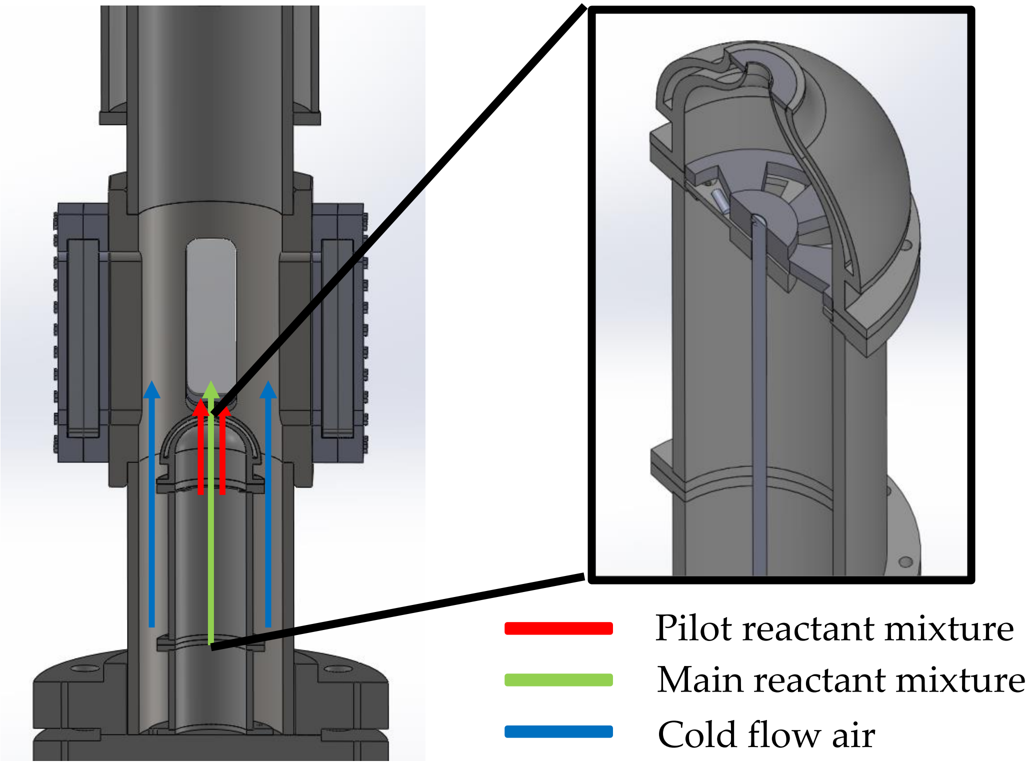
EXPERIMENTAL FACILITY

Piloted Bunsen flame

- Contoured nozzle
- Annular pilot flame to stabilize the main flame
  - U= 4-70 m/s
  - Re_{Bulk} up to 100,000
  - Multiple burner diameters

Pressure vessel

- Data up to 20 atm
- Optical access for diagnostics
- Cold and pre-heated flow
- Fully remotely operable



🟥 Pilot reactant mixture
🟩 Main reactant mixture
🟦 Cold flow air

GEORGIA TECH TURBULENT FLAME SPEED DATABASE

Dataset 1

H_2/CO (+ CH_4)

Constant $S_{L,0}$ (12 mm and 20 mm)
Constant φ(20 mm)

Dataset 2

$H_2/CO/CH_4/N_2$

Constant φ (12 mm)

Dataset 3

H_2/CH_4

Constant $S_{L,0}$ (12 mm)

Dataset 4

H_2/CH_4

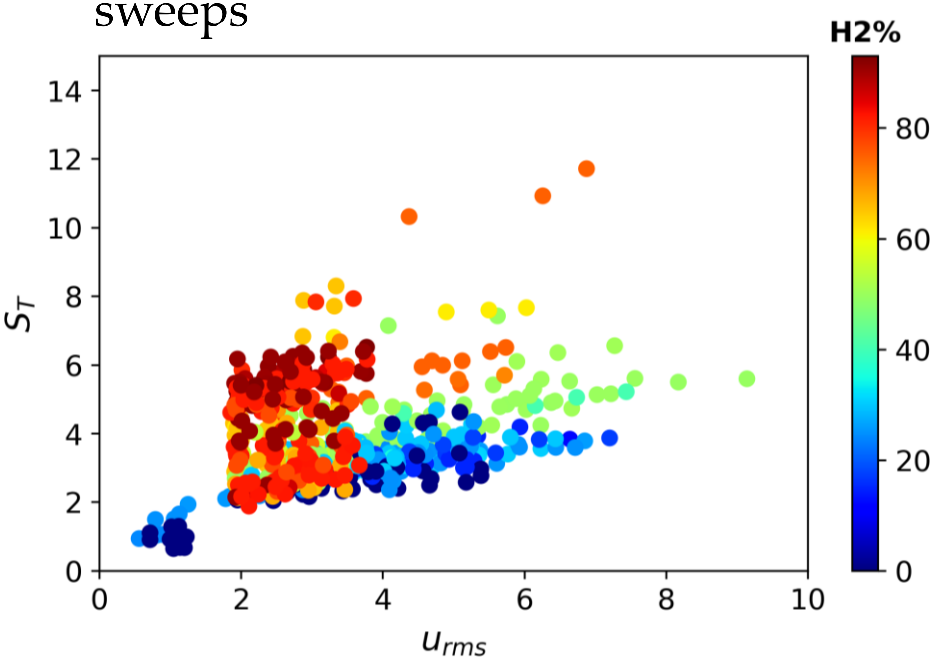
Constant $S_{L,0}$ (12 mm)
Constant φ and H_2 (12 mm
Constant T_{ad}

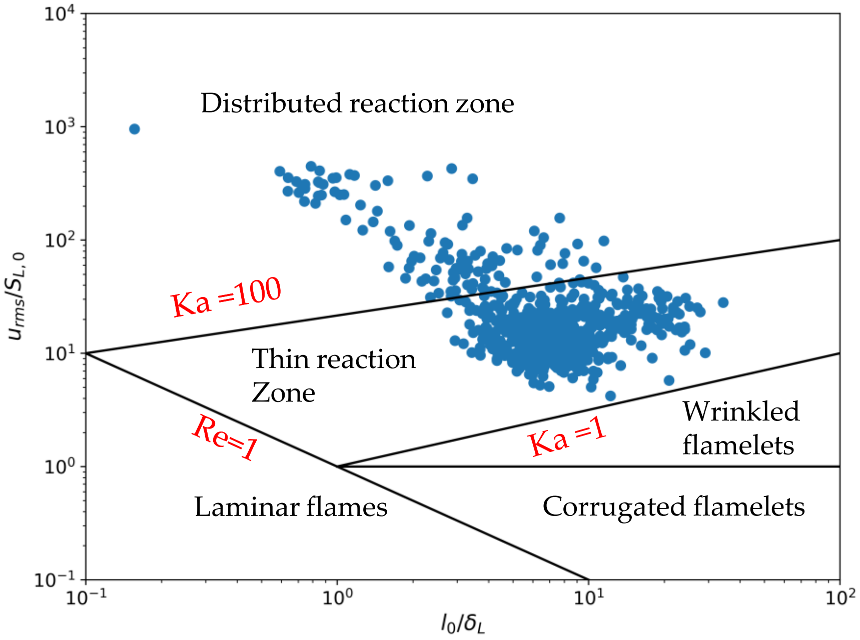
Parameter	Dataset 1	Dataset 2	Dataset 3	Dataset 4
Pressure (atm)	1-20	1-20	1-16	1-15
Preheat Temperature (K)	300	350-500	300-400	300-400
Equivalence Ratio	0.4-0.9	0.34-0.85	0.6-0.9	0.39-0.94
Hydrogen Fraction (% Vol)	0,30,90	27-87	0-50	0-92
Inlet Velocity (m/s)	4-50	40-50	30	10-50
Turbulence Intensity	0.67-14.5	4.4-10.3	3.4-5.6	0.55-9.3
Burner Diameter	12,20	12	12	12

DATA ACQUIRED SINCE LAST YEAR (DATASET 4)

Lean high pressure high hydrogen flame data – highly stretch sensitive cases

Constant parameter sweeps of importance – Constant T_{ad}, $S_{L,0}$, φ sweeps





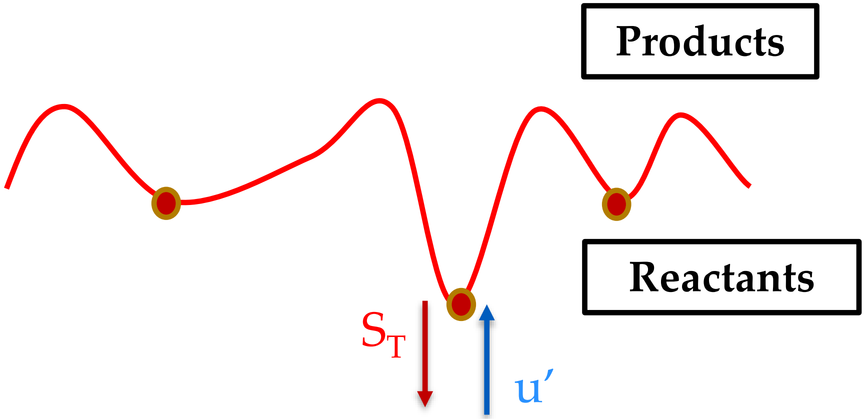
Borghi-Peters diagram

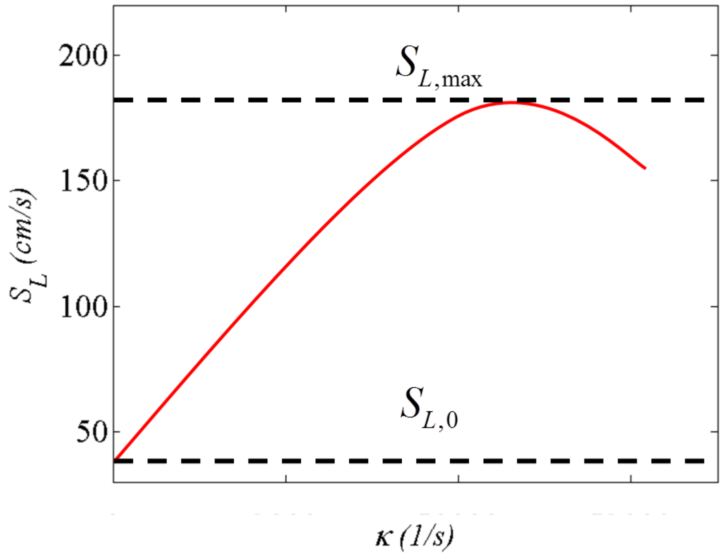
TURBULENT FLAME SPEED DATABASE: SCALING

DISCUSSION

- One parameter scaling

$$\frac{S_T}{S_{L,max}} \sim f\left(\frac{u'_{rms}}{S_{L,max}}\right)$$



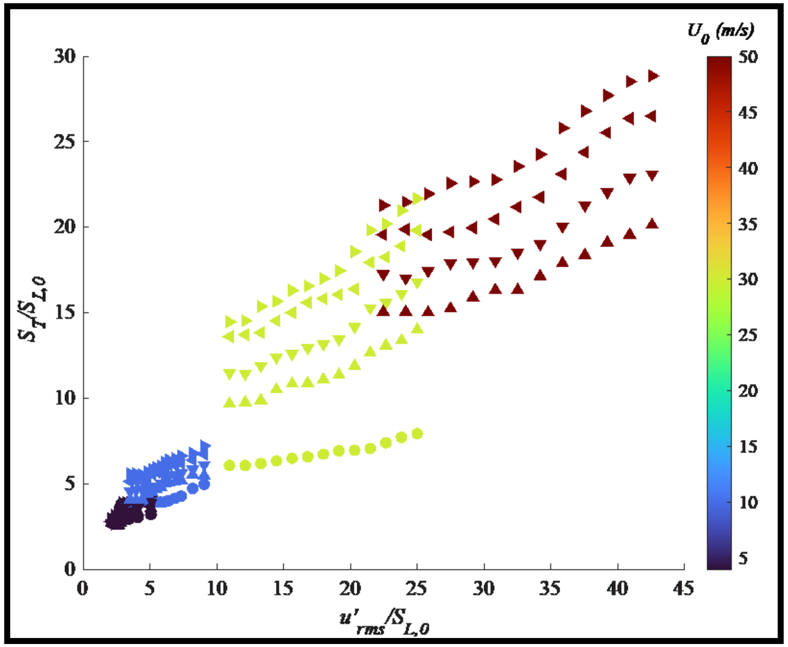


NORMALIZING FLAME PARAMETERS: $S_{L,0}$ and $S_{L,max}$

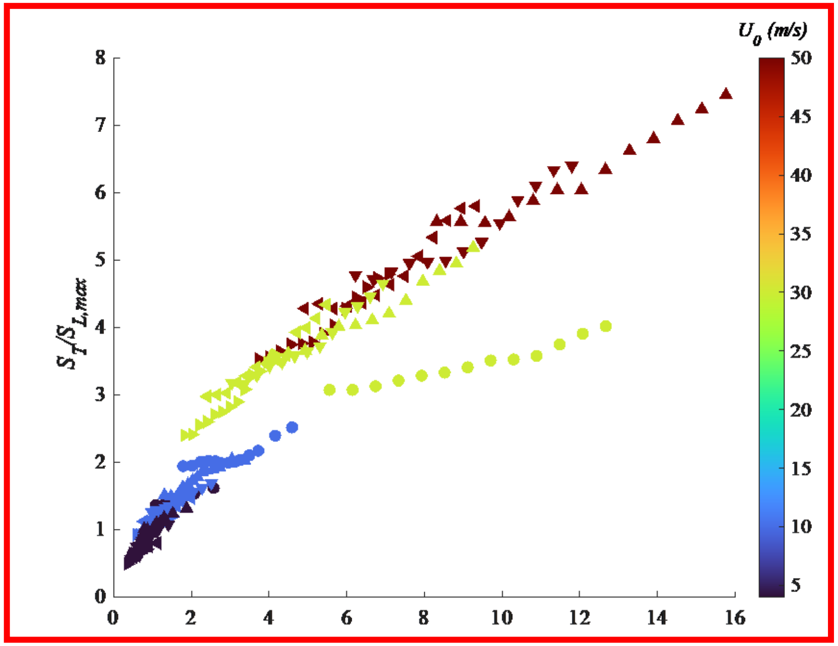
$\{p = 1\, atm, T_u = 300\, K, S_{L,0} \sim 34\, cm/s\}$

(H_2%)	0	30	50	70	90
	●	▲	▼	◀	▶

$S_{L,0}$ Normalization

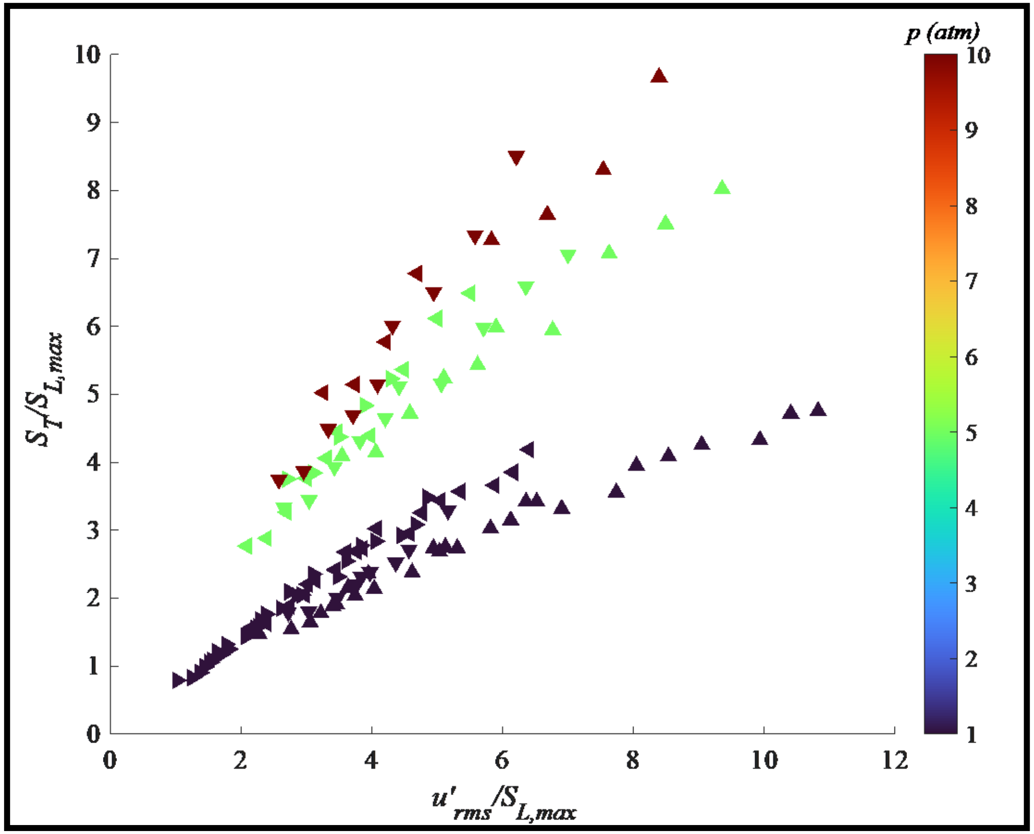


$S_{L,max}$ Normalization



Dataset 1: $S_{L,max}$ Scaling Captures H_2 Effects

$S_{L,max}$ SCALING- VARIABLE PRESSURE

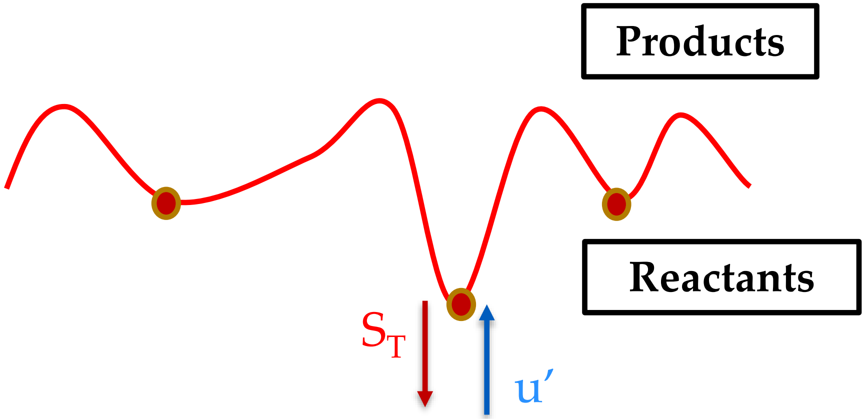


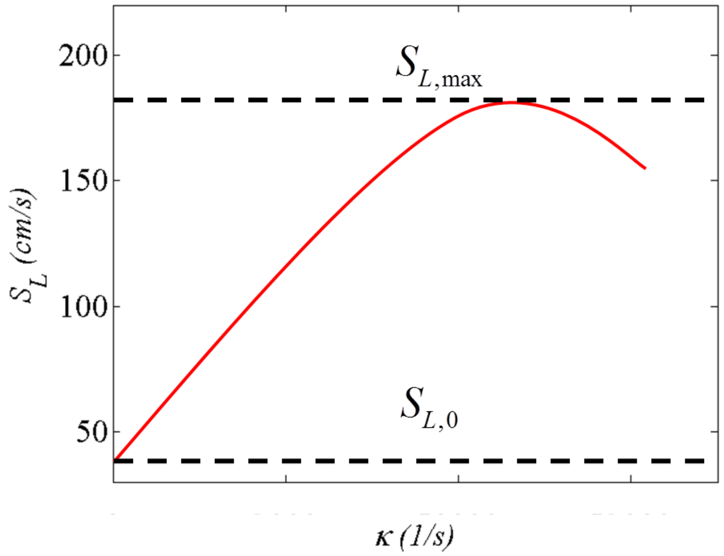
(H_2%) 0 30 50 70 90

● ▲ ▼ ◀ ▶

Dataset 1: $S_{L,max}$ Scaling does not capture pressure effects

DISCUSSION





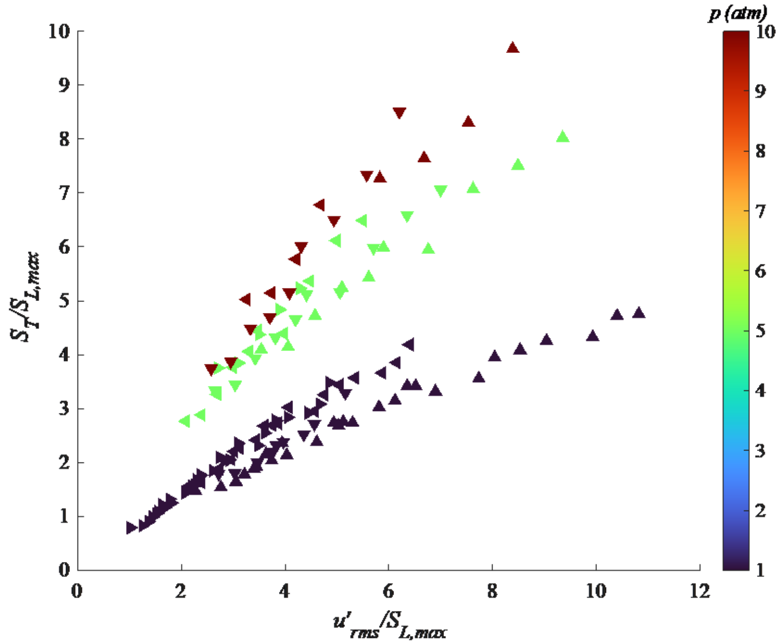
- Two parameter scaling:

$$\frac{S_T}{S_{L,max}} \sim f\left(\frac{u'_{rms}}{S_{L,max}}, X_2\right)$$

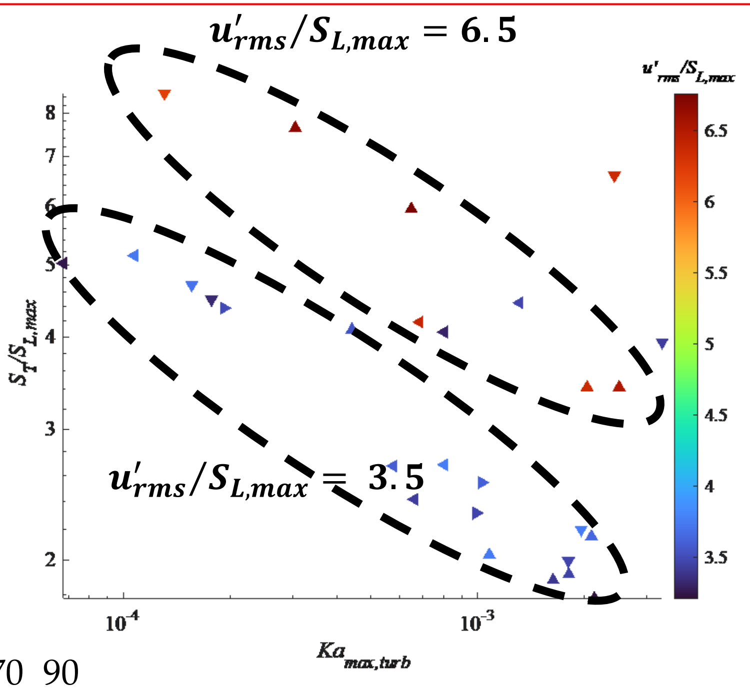
- Proposed ideas:
  - Time scale ratio
  - Reynolds number

TWO PARAMETER SCALING: TIME SCALE RATIO

$S_{L,max}$ *Normalization*



Time Scale Ratio at $\frac{u'_{rms}}{S_{L,max}}$ *of* $3.5, 6.5$


$u'_{rms}/S_{L,max} = 6.5$

$u'_{rms}/S_{L,max} = 3.5$

(H_2%)	0	30	50	70	90
	●	▲	▼	◀	▶

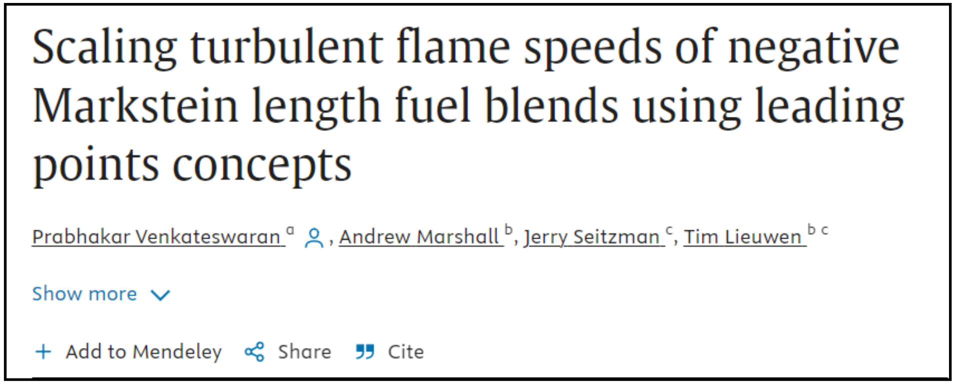
Dataset 1: Pressure effects can be correlated to a time scale ratio at fixed $u'_{rms}/S_{L,max}$

TWO PARAMETER SCALING: TIME SCALE RATIO

- Correlation of data from 4 groups with varying hydrogen and pressure content led to proposed scaling:

$$\frac{S_T}{S_{L,max}} \propto f\left(\frac{u'_{rms}}{S_{L,max}}, Ka\right)$$

- Continued analysis, nonetheless, has revealed difficulty of correlation across increasingly broad set of conditions



Scaling turbulent flame speeds of negative Markstein length fuel blends using leading points concepts

Prabhakar Venkateswaran [a], Andrew Marshall [b], Jerry Seitzman [c], Tim Lieuwen [b c]

P. Venkateswaran , A.D. Marshall, J.M. Seitzman, T.C.Lieuwen, Scaling turbulent flame speeds of negative Markstein length fuel blends using leading points concepts, Combustion and Flame, Volume 162, Issue 2, 2015,Pages 375 -387

REFERENCE FLAME SPEED ANALYSIS

FINDING A REFERENCE NORMALIZING FLAME SPEED

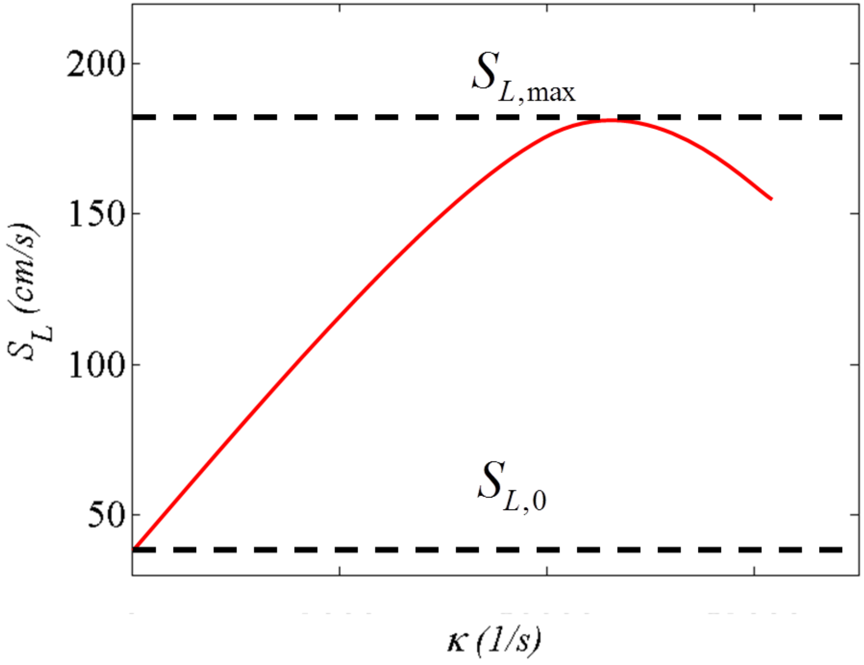
- Prior work has essentially focused on identifying a reference laminar burning velocity, $\boldsymbol{S_{L,ref}}$

$$\frac{S_T}{S_{L,ref}} \sim f\left(\frac{u'_{rms}}{S_{L,ref}}\right)$$

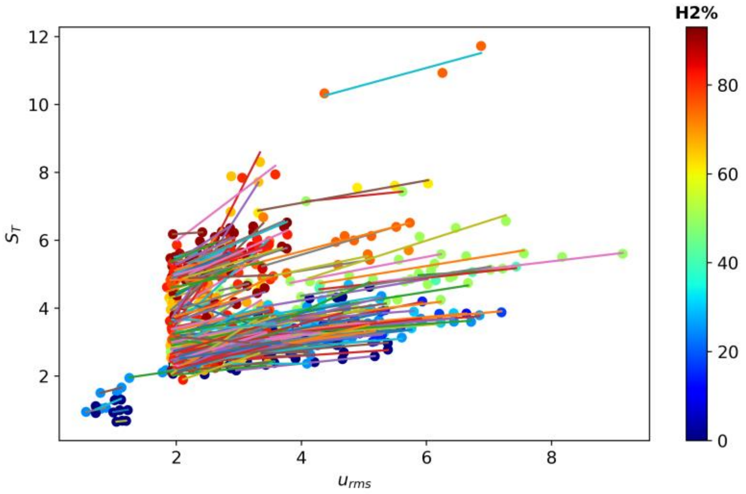
- **If hypothesis is correct, then we should be able to bound $\boldsymbol{S_{L,ref}}$:**

$$\boldsymbol{S_{L,0} < S_{L,ref} < S_{L,max}}$$

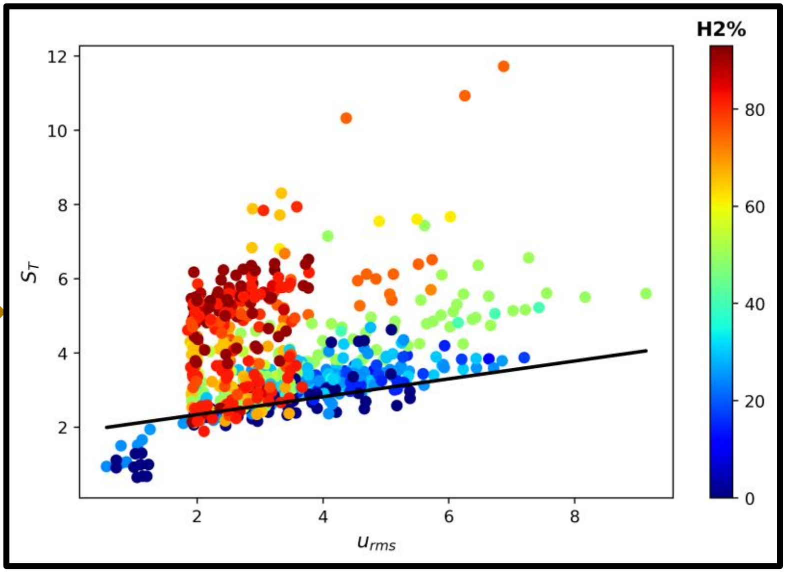
$$\boldsymbol{0 < \frac{S_{L,ref} - S_{L,0}}{S_{L,max} - S_{L,0}} < 1}$$



COMPUTING $S_{L,ref}$



$\boldsymbol{S_{L,ref}}$ to collapse data onto a single reference data set

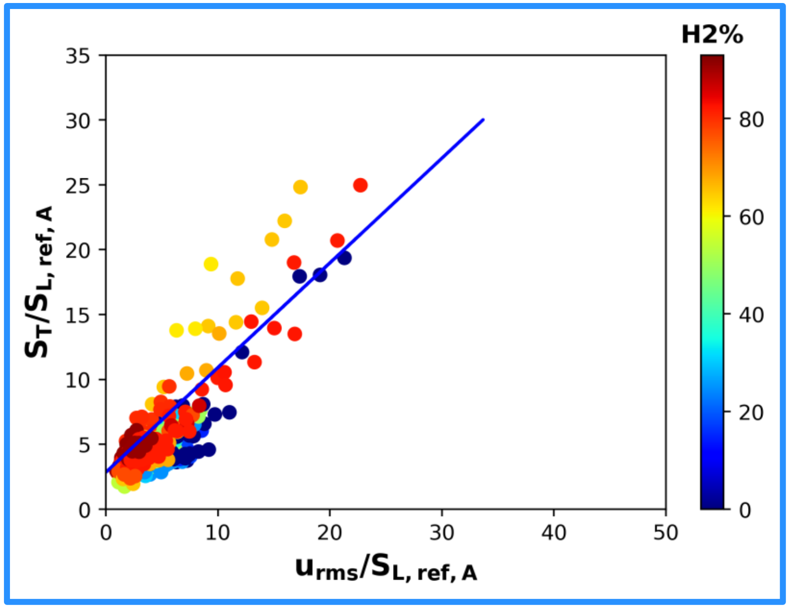


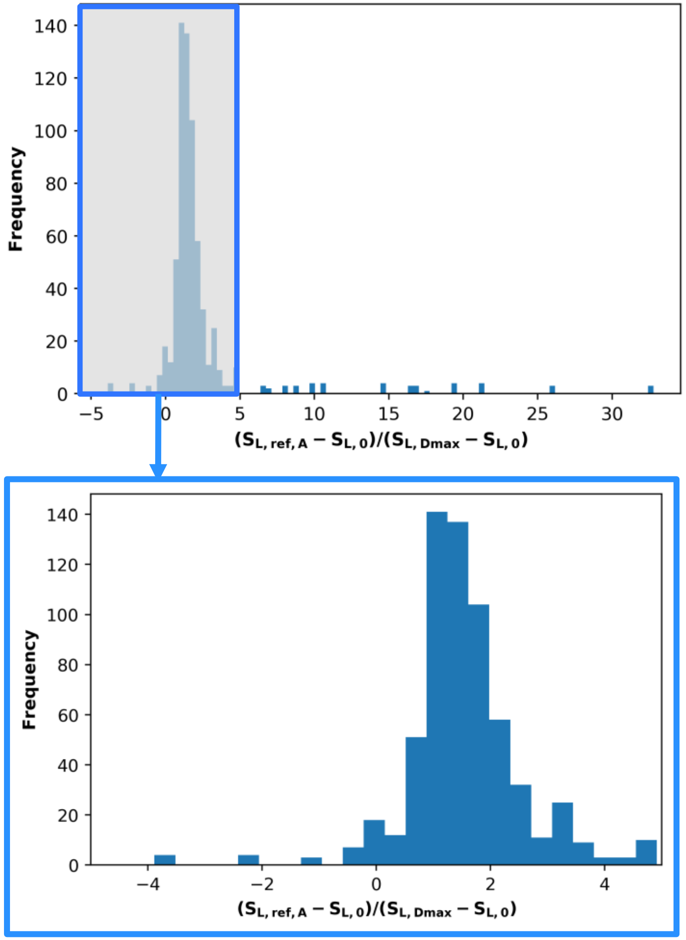
To find values of reference flame speed that will help collapse all sets of data, a reference value is chosen. $\boldsymbol{S_{L,ref}}$ is calculated based on the following reference data sets

(A)P=10Bar, T=360K, U0 ~ 20m/s, H2=91%, Φ=0.51

(B) P=2Bar, T=300K, U0 ~ 30m/s, H2=0%, Φ=0.74

(1) COMPUTING $S_{L,ref\,A}$: DATA NORMALIZED BY $S_{L,ref\,A}$ (HIGHLY STRETCH SENSITIVE FLAME)





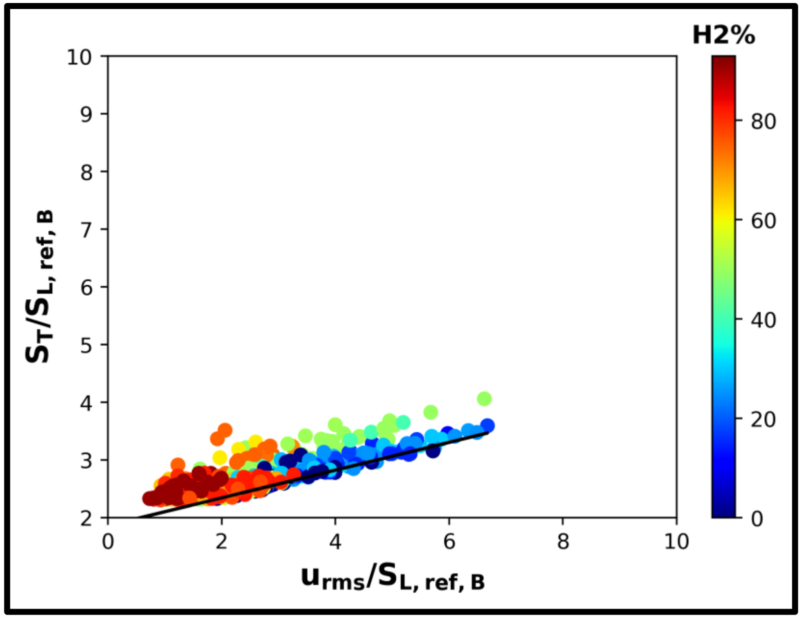
$$\frac{S_{L,ref\,A}-S_{L,0}}{S_{L,max}-S_{L,0}} > 1$$

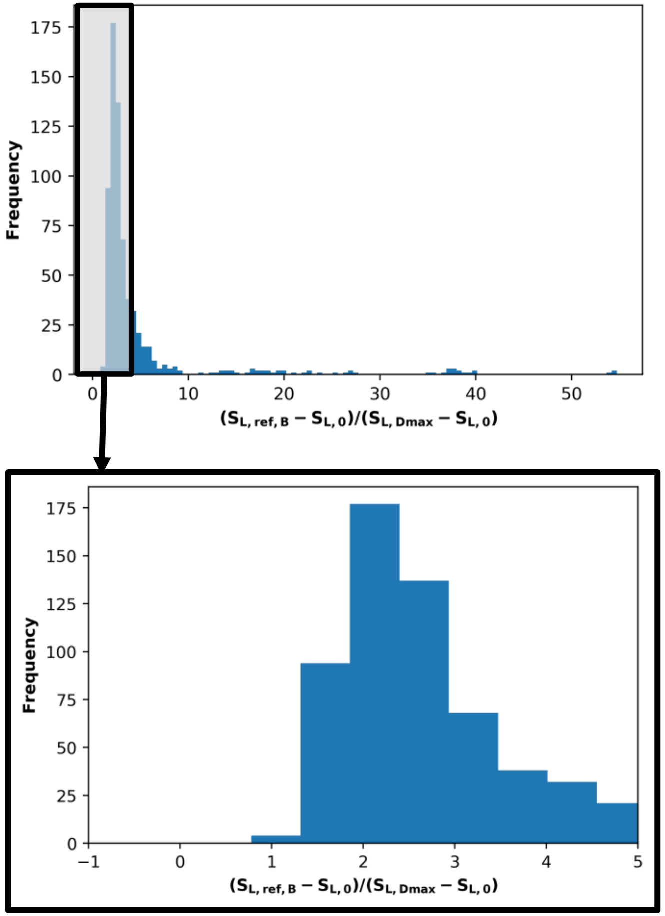
$$\boldsymbol{S_{L,ref\,A} > S_{L,max}}$$

$$\frac{S_{L,ref\,A}-S_{L,0}}{S_{L,max}-S_{L,0}} < 0$$

$$\boldsymbol{S_{L,ref\,A} < S_{L,0}}$$

(2) COMPUTING $S_{L,ref\,B}$: DATA NORMALIZED BY $S_{L,ref\,B}$ (Ma ~0)





$$\frac{S_{L,refB}-S_{L,max}}{S_{L,max}-S_{L,0}} >> 1$$

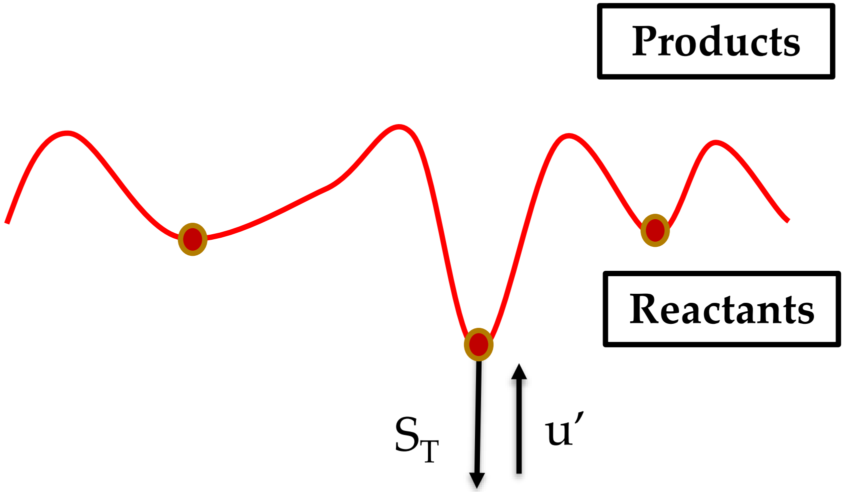
$S_{L,refB} >> S_{L,max}$

$$\frac{S_{L,refB}-S_{L,max}}{S_{L,max}-S_{L,0}} > 0$$

$S_{L,refB} > S_{L,0}$

TENTATIVE CONCLUSIONS

- Analysis in previous slides clearly indicates that $S_{L,ref}$ alone is insufficient to capture fuel and pressure effects



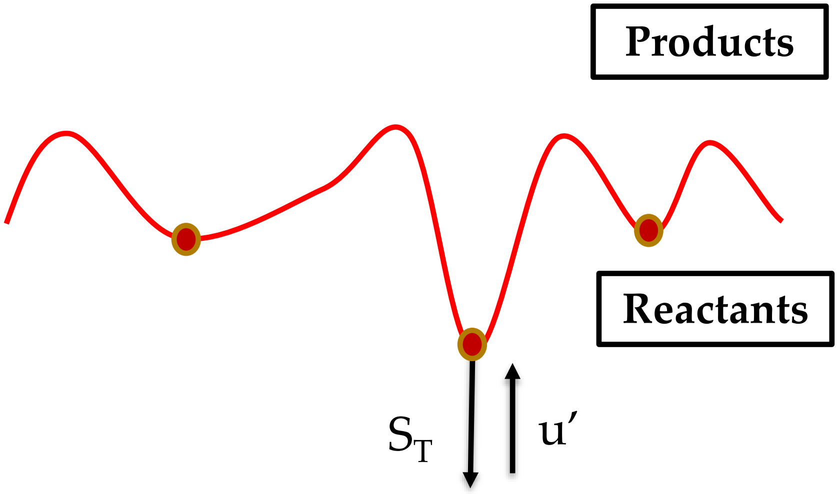
DISTURBANCE VELOCITY INFLUENCE ON TURBULENT FLAMES

- Scalings use RMS turbulence intensity to scale turbulence burning velocities
- For a given u'_{rms}, Reynolds number also influences:
  - Range of length/time scales disturbing flame, and therefore associated range of flame wrinkling length scales
  - Range in instantaneous u' values experienced by flame

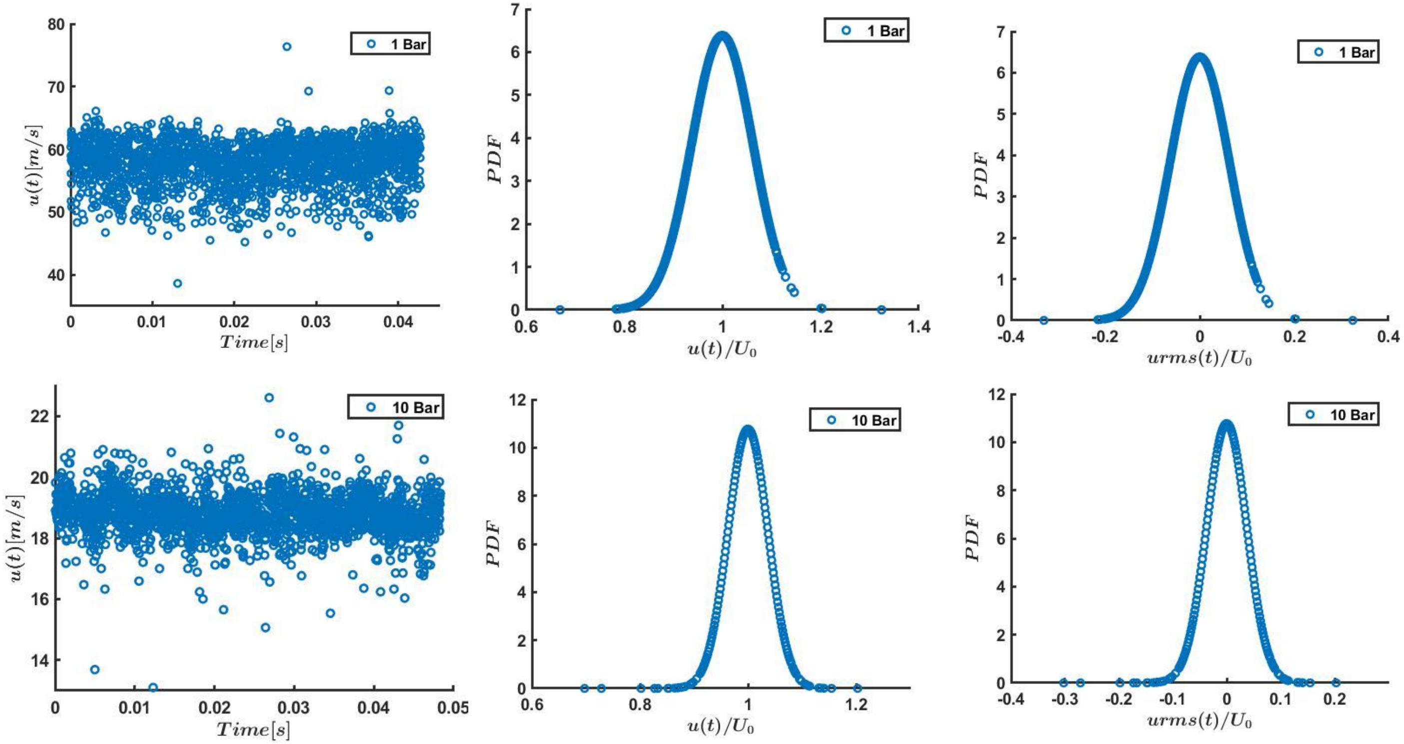
Potential scaling approaches:

$$\frac{S_T}{S_{L,ref}} \propto f\left(\frac{u'_{rms}}{S_{L,ref}}, Re\right)$$

$$\frac{S_T}{S_{L,ref}} \propto f\left(\frac{u'_{ref}}{S_{L,ref}}\right)$$



PRILIMINARY STUDIES
HIGHER ORDER VELOCITY MOMENTS AT PRESSURE



P	Re	Kurtosis
1	32,800	2.96
5	78,000	2.96
10	15,600	8.62

PLANNED WORK OVER NEXT YEAR

- Above discussion clearly indicates that the effect of thermodynamic parameters at gas turbine conditions on turbulent flame speed is inconclusive

- Our new work has demonstrated that prior approaches to capture fuel composition, pressure, and preheat temperature effects through reference flame speed is problematic

- Next steps:
    - Explore approaches for incorporating $S_{L,ref}$ and u'_{ref} correlations simultaneously
    - Obtain more detailed measurements of higher order velocity moments to utilize in scaling measurements
    - Continue expanding S_T database - H_2%, pressure, preheat, equivalence ratio