High-temperature laminar burning velocity experiments in a shock tube:

LBV, temperature, and species measurements

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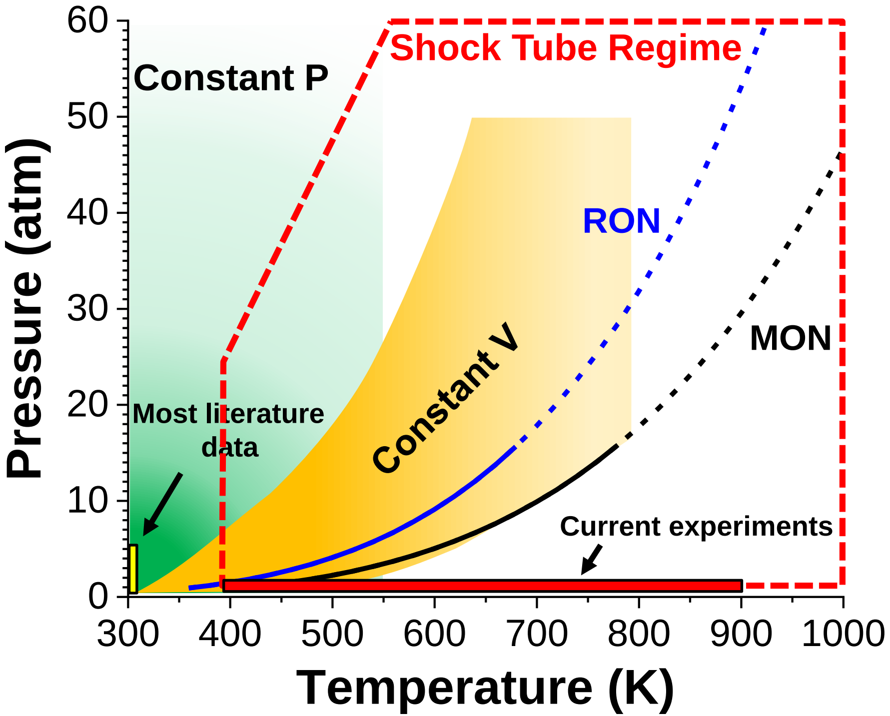
Motivation: Why study flames in a shock tube?



- Limited flame speed data at high unburned gas T (>500 K)
- Shock tubes are ideal reactors for studying high-temperature combustion phenomena
  - Tunable T & P
  - Near-instantaneous heating (well-defined time zero)

Overview of Experiments

Goal: Use a shock tube to extend the temperature regime accessible by existing laminar flame speed measurement approaches

Laminar flame speed experiments in a shock tube

I. Small Hydrocarbons

High-temperature flame speed measurements: CH_4, C_2H_6, C_3H_8

II. Laser Diagnostics

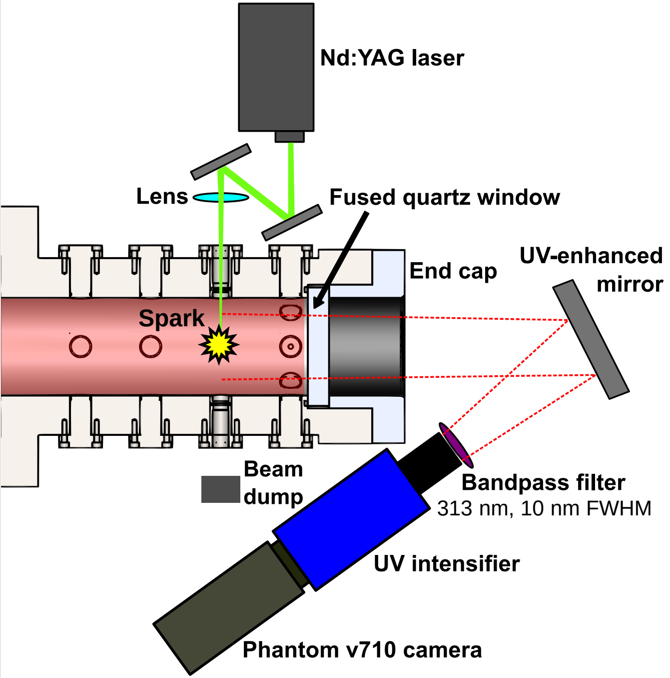
Temperature and species (CO_2 & H_2O) measurements in C_2H_6-air flames

III. NTC Regime

Iso-octane flame speed measurements in the NTC regime

First, the approach…

Experimental Setup: Laminar flames in a shock tube



Laminar flames are initiated behind reflected shock waves via laser-induced spark ignition

Shock tube

- 11.53-cm inner diameter
- 3.63-m driver, 9.73-m driven
- Test times: 3.5-15 ms (N_2, He, CO_2 driver)

Nd:YAG laser

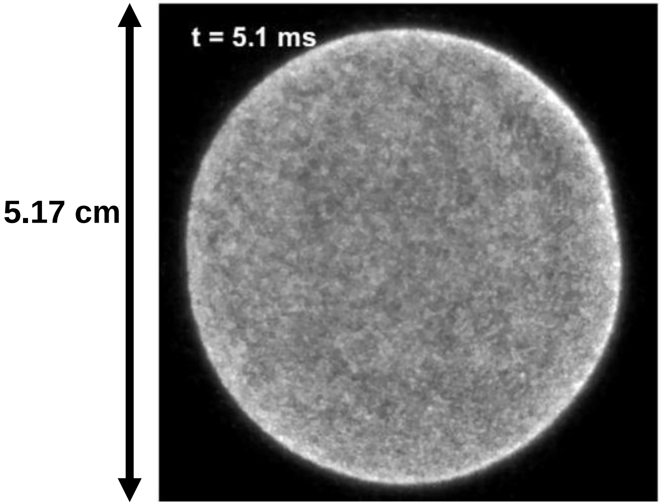
- 532 nm, 5 ns pulse, ~18 mJ/pulse

High-speed OH* emission (306 nm) imaging

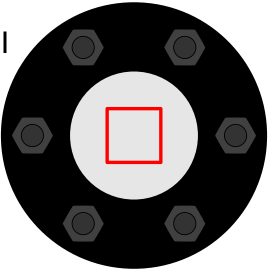
- UV-intensified, endwall emission

OH* Emission Images

Example: raw images (OH* emission, 306 nm)
C_2H_6 in air, Φ = 1.0, **488 K, 1.0 atm**



Field of View:
Shock tube endwall



- UV-intensified OH* emission imaging
- 10-40 kHz frame rate
- 90-140 µm/pixel

- Field of view:
  - 5.17 x 5.17 cm (384 x 384 pixels)
  - 10 cm from shock tube endwall

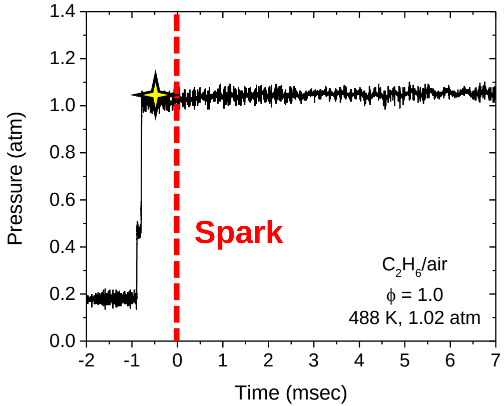


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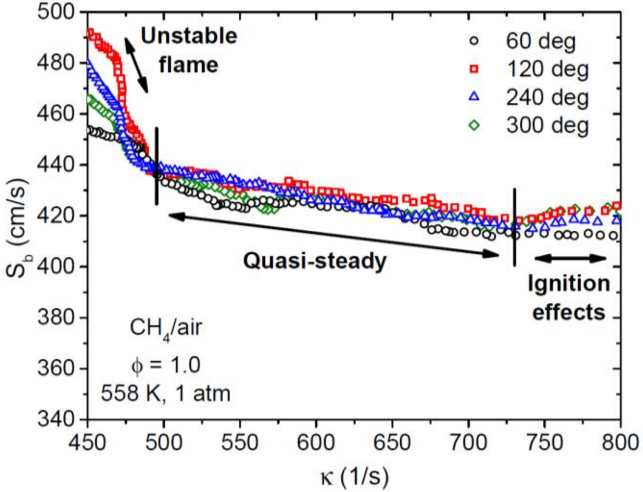
Image Processing



- Local stretch rate (κ) and burned flame speed (S_b) calculated at regular intervals around circumference of flame
- Quasi-steady subset of S_b vs κ data selected for unstretched flame speed extrapolation [1]

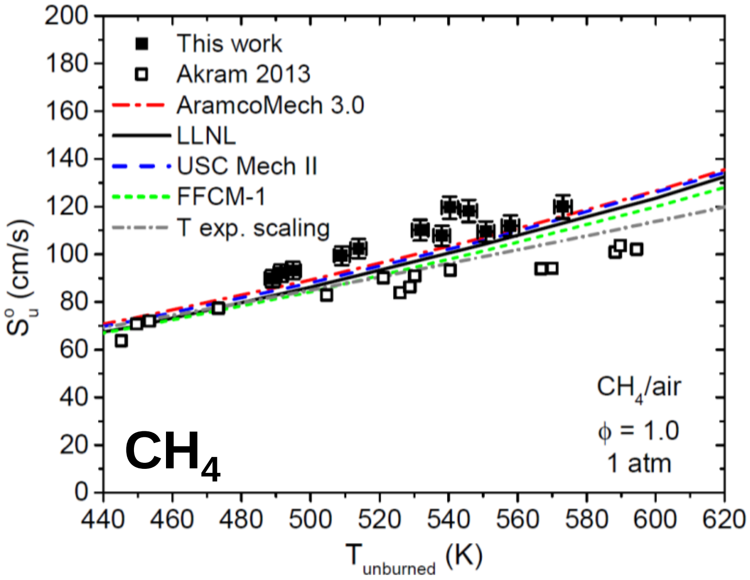
$$S_b^2 - S_b^o S_b = -S_b^o L_b \kappa \qquad \rho_u S_u^o = \rho_b S_b^o$$

[1] M.L. Frankel, G.I. Sivashinsky, Combust. Sci. Technol. 31 (3-4) 131-138 (1983).

Mixture	CH_4/air	C_2H_6/air
Φ	1.0	1.0
$T_{unburned}$ (K)	489-573 K	449-537 K
Pressure (atm)	1.0 ± 0.05	1.0 ± 0.05

I. Small Hydrocarbons

CH_4 and C_2H_6 flame speed measurement results:



The high-temperature C_2H_6 flame speed results have not yet been published, and have therefore been removed from the publicly distributed version of this talk.

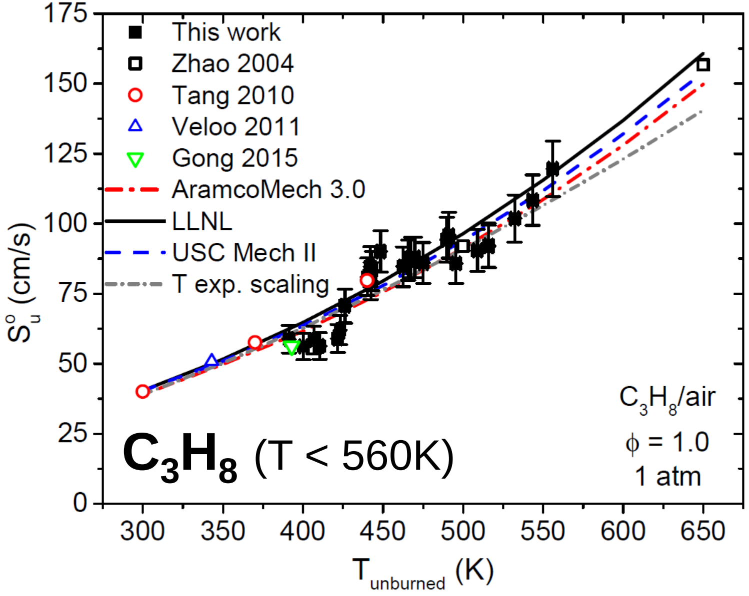
- CH_4 results are 5-10% higher than model results
  - Only one other high-T CH_4 data set in literature
- C_2H_6 results show close agreement with USC Mech results, higher disagreement with Aramco results

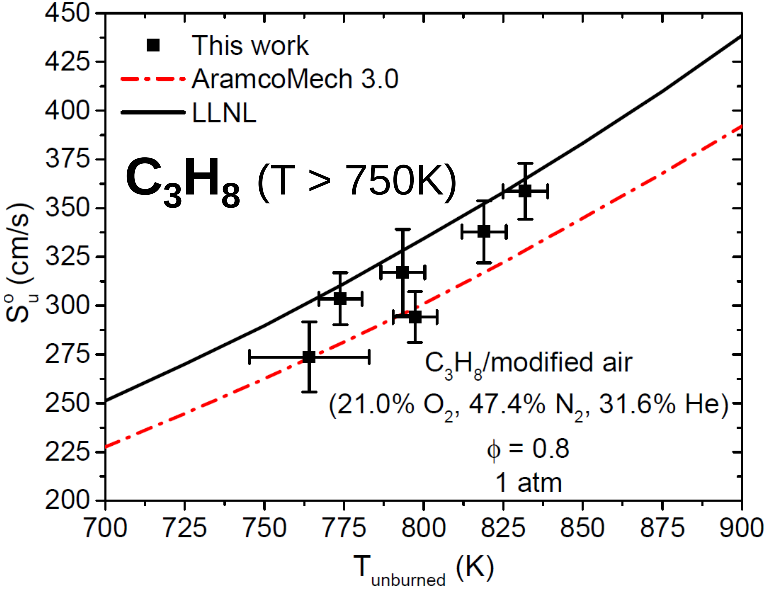
The CH_4 flame speed results are available in: A.M. Ferris, A.J. Susa, D.F. Davidson, R.K. Hanson, Combust. Flame, 2019, DOI: 10.1016/j.combustflame.2019.04.007

Mixture	C_3H_8/air	C_3H_8/modified-air
Φ	1.0	0.8
$T_{unburned}$ (K)	391-556 K	764-832 K
Pressure (atm)	1.0 ± 0.05	1.0 ± 0.05

I. Small Hydrocarbons

C_3H_8 flame speed measurement results:



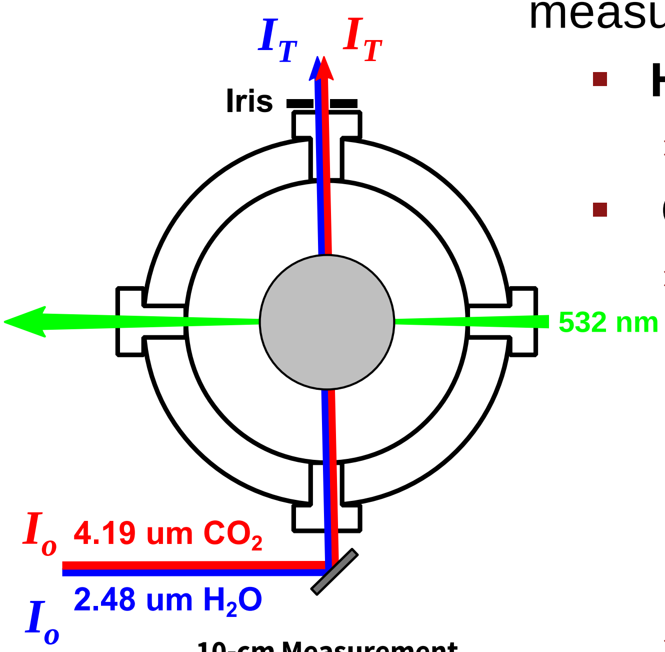


- Results show excellent agreement with model and (available) literature results
- Disagreement between model results at higher temperatures highlights need for high-T flame speed validation data

The C_3H_8 flame speed results are available in: A.M. Ferris, A.J. Susa, D.F. Davidson, R.K. Hanson, Combust. Flame, 2019, DOI: 10.1016/j.combustflame.2019.04.007

II. Laser Diagnostics

- Two time-multiplexed, scanned-direct absorption diagnostics were used to measure temperature, CO_2, and H_2O in C_2H_6-air flames:
  - **H_2O:**
    - 1 transition near 2.48 µm (4029.52 cm^{-1}) [2]
  - **CO_2 and Temperature:**
    - 2 transitions near 4.19 µm (2384.19, 2384.33 cm^{-1}) [3]



10-cm Measurement Plane View

Beer-Lambert Relation:

Transmitted
Mole fraction
Path length

$$\alpha_\nu = -\ln\left(\frac{I_T}{I_o}\right)_\nu = \frac{X_{Abs}P}{RT}\sigma_\nu L$$

Incident
Absorbance
Absorption cross-section

- OH* emission images used to determine time-dependent path length, L

[2] Goldenstein et al., J. Quant. Spectrosc. Radiat. Transf. 130 (2013) 100-111.
[3] Girard et al., Combust. Flame 178 (2017) 158-167.

II. Laser Diagnostics: T measurement results

Note: the temperature laser absorption results have not yet been published; the corresponding plots have therefore been removed from the publicly distributed version of this talk.

Time-resolved temperature measurements show:

- Burned gas temperature increases for the first 5-6 ms, then ultimately plateaus to a final, equilibrium burned gas temperature
- Constant long-time temperature indicates minimal radiative losses

Equilibrium burned gas temperature measurements, measured for each ethane-air flame experiment (1 atm, 449-537 K), show:

- Excellent agreement with AramcoMech 3.0 and USC Mech II modeled results across the entire temperature range (within ±3.2% uncertainty)

II. Laser Diagnostics: Mole fraction results (equilibrium)

Note: the CO_2 and H_2O laser absorption results have not yet been published; the corresponding plots have therefore been removed from the publicly distributed version of this talk.

Equilibrium CO_2 mole fraction measurements show:

- Good agreement with model results (AramcoMech 3.0, USC Mech II), within uncertainty bounds (±9.2%)

Equilibrium H_2O mole fraction measurements show:

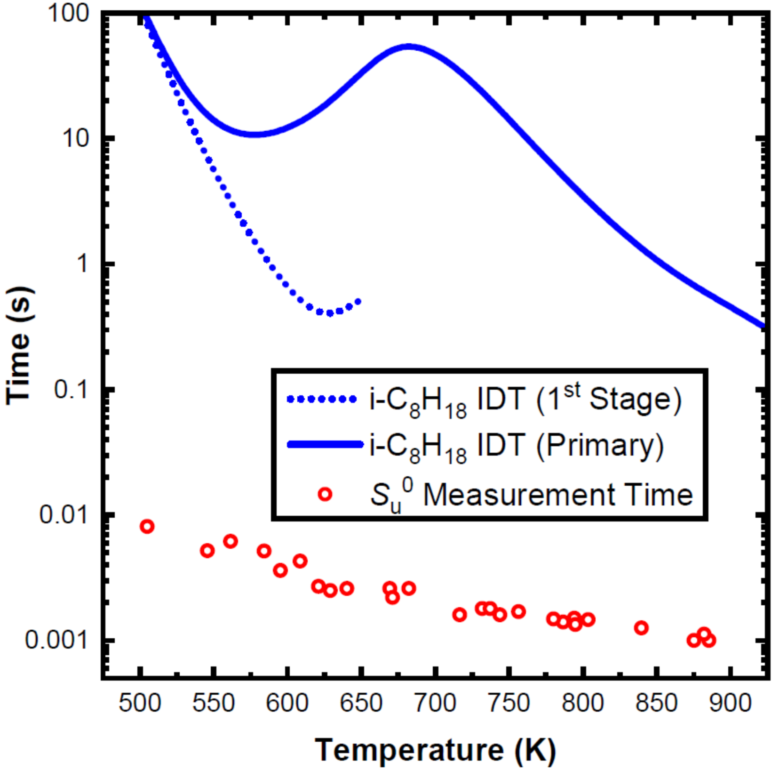
- Satisfactory agreement with model results, within uncertainty bounds (±10%)
  - Higher scatter likely due to background signal fluctuations

III. NTC Regime: *iso*-octane

***Iso*-octane burning velocity measurements in $O_2/N_2/He$:**

- $\Phi = 0.9$ fuel in 18% O_2, 41% N_2, 41% He
- 500-900 K, 1 atm (±5%)

IDT >> experiment time: no pre-flame reactions expected in bulk gas



III. NTC Regime: *iso*-octane

Iso-octane burning velocity measurements in $O_2/N_2/He$:

- $\Phi = 0.9$ fuel in 18% O_2, 41% N_2, 41% He
- 500-900 K, 1 atm (±5%)

1. Burning velocity increases w/ T (500-600 K)
   - Results 20-30% low of simulation
2. Burning velocity T dependence stronger than modeled (600-750 K)
3. Negative T dependence of burning velocity (750-820 K)
4. Excellent model agreement, then stronger T dependence than modeled (820-900 K)

The NTC-regime *iso*-octane flame speed results have not yet been published, and have therefore been removed from the publicly distributed version of this talk.

The NTC-regime *iso*-octane flame speed results show different behaviors over 4 distinct temperature ranges

First direct experimental evidence of NTC flame speed behavior

Summary & Future Work

Summary:

- High-temperature CH_4, C_2H_6, and C_3H_8 flame speeds show close agreement with literature and model results
- Laser absorption diagnostics were successfully deployed to measure temperature, CO_2, and H_2O
- *Iso*-octane flame speed results show evidence of NTC behavior – the first such experimental observation

Future work:

- Extend high-temperature flame speed data sets
  - Additional temperatures, pressures, equivalence ratios
- Use quantitative laser diagnostics to probe NTC flame speed behavior (cool flames?)
- Simulate results as spherically expanding flames using DNS

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Questions?