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: CH₄, C₂H₆, C₃H₈

II. Laser Diagnostics
Temperature and species (CO₂ & H₂O) measurements in C₂H₆-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 (N₂, He, CO₂ 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$_2$H$_6$ in air, $\Phi = 1.0$, 488 K, 1.0 atm

- 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
Local stretch rate ($\kappa$) and burned flame speed ($S_b$) calculated at regular intervals around circumference of flame

- Quasi-steady subset of $S_b$ vs $\kappa$ data selected for unstretched flame speed extrapolation [1]

\[
S_b^2 - S_b^0 S_b = -S_b^0 L_b \kappa \\
\rho_u S_u^0 = \rho_b S_b^0
\]

I. Small Hydrocarbons

CH$_4$ and C$_2$H$_6$ flame speed measurement results:

<table>
<thead>
<tr>
<th>Mixture</th>
<th>CH$_4$/air</th>
<th>C$_2$H$_6$/air</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$T_{unburned}$ (K)</td>
<td>489-573 K</td>
<td>449-537 K</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>1.0 ± 0.05</td>
<td>1.0 ± 0.05</td>
</tr>
</tbody>
</table>

- CH$_4$ results are 5-10% higher than model results
  - Only one other high-T CH$_4$ data set in literature

- C$_2$H$_6$ results show close agreement with USC Mech results, higher disagreement with Aramco results

The high-temperature C$_2$H$_6$ flame speed results have not yet been published, and have therefore been removed from the publicly distributed version of this talk.

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
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

<table>
<thead>
<tr>
<th>Mixture</th>
<th>C_3H_8/air</th>
<th>C_3H_8/modified-air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>T_unburned (K)</td>
<td>391-556 K</td>
<td>764-832 K</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>1.0 ± 0.05</td>
<td>1.0 ± 0.05</td>
</tr>
</tbody>
</table>
II. Laser Diagnostics

- Two time-multiplexed, scanned-direct absorption diagnostics were used to measure temperature, CO$_2$, and H$_2$O in C$_2$H$_6$-air flames:
  - **H$_2$O:**
    - 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]
  - OH* emission images used to determine time-dependent path length, L

Beer-Lambert Relation:

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

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 CO₂ and H₂O laser absorption results have not yet been published; the corresponding plots have therefore been removed from the publicly distributed version of this talk.

Equilibrium CO₂ mole fraction measurements show:

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

Equilibrium H₂O 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 ($\pm 5\%$)

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 ($\pm$ 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)

**First direct experimental evidence of NTC flame speed behavior**

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.
Summary & Future Work

Summary:

- High-temperature CH$_4$, C$_2$H$_6$, and C$_3$H$_8$ flame speeds show close agreement with literature and model results
- Laser absorption diagnostics were successfully deployed to measure temperature, CO$_2$, and H$_2$O
- *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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  - Dr. Ralph Anthenien

Questions?