Spherical Flame Acceleration in Lean Hydrogen-Air Flames

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Accidental Explosions
Motivation – Accidental Explosions

- Flame propagation velocity key parameter to determine pressure that develop
- Cell formation can significantly increase propagation velocity
- Need a better understanding of how cells form and growth with flame
  - Bradley et al. 2001, Kim et al., 2015

Limited data on atmospheric pressure flames, especially at large-scale
Background – Darrieus-Landau Instability

- Intrinsic instability due to expansion of burned gas

- Extensively studied
  - Experimentally
    - Manton et al. (1952), Bradley and Harper (1994), Clanet and Searby (1998), Law et al. (2005)…
  - Analytically
Background – Spherical Flames

- Initially flame stabilized by curvature and stretch
- At a critical radius, $R_0$, cells spontaneously form on flame surface
- Cell formation accompanied by rapid flame acceleration
Background – Spherical FA

- Acceleration continues indefinitely with increasing radius

- Self-similar theory
  - Gostintsev et al. (1988)
    - Correlated large scale data
    - Found: $R = R_0 + At^\alpha$
  - Acceleration mechanism explained using fractal argument
Present Study – Hydrogen-Air

- Why lean hydrogen-air?
  - Strong thermal-diffusive instability
    - Small critical radius
  - Larger increases in flame speed for the same flame size

- Examined lean hydrogen-air concentrations
  - $\phi = 0.3 - 0.6$
Experimental Setup

- 64 m$^3$ vented enclosure (4.6 x 4.6 x 3 m$^3$)
- Constant pressure
- Quiescent mixtures
- Weak ignition source
Visualizing Hydrogen-Air Flames

- Direct optical measurements not possible
- Traditional schlieren not feasible at large scale
- Alternate method needed
Background Oriented Schlieren

- Background Pattern
- Imaged Media
- Deflection
- Camera

Background Pattern
Background Oriented Schlieren

Raw Images → BOS Image
FM Global

Background Oriented Schlieren
Front Tracking

- Maximize images into virtual open shutter
- Difference images across multiple frames
- Calculate radius from flame cross-section
Temporal Smoothing

- Average flame surface over time (multiple images)
- Resize flame to a common length scale to eliminate motion blur
Effect of Concentration

$\phi = 0.33$

$\phi = 0.46$

$\phi = 0.57$
Results – Hydrogen-air $\phi = 0.49$

- Plot of flame speed vs. stretch rate
  \[ \gamma = \frac{2}{R} \frac{dR}{dt} \]

- Linear stretch extrapolation to obtain LBV

- Critical radius, $R_0$, from $\gamma_0$

\[ \gamma_0 = \frac{2}{R_0} \frac{dR_0}{dt} \]
Results

- Laminar burning velocity
  - Good agreement with past studies

![Graph showing laminar burning velocity comparison with past studies](image-url)
## Results

- **Critical radius**
  - \( R_0 \) decreased linearly with \( \mathcal{L}_M \) (and \( \phi \))
Discussion

- Flame self-acceleration
  - Normalized curves all collapse to single relation
  - No oscillations observed

\[ u^* = \left( \frac{R}{R_0} \right)^{0.24} \]
Discussion

- Fractal excess constant across full range
  \[ \beta = 0.243 \pm 0.005 \]

- Equivalent to fractal exponent \( \alpha = 1.32 \)
Discussion

- Flame self-acceleration results in large increase in $u_{\text{eff}}$
- Flame velocity doubles when $R/R_0 = 16$ ($R = 0.3 - 0.5$ m)
Summary/Conclusions

- BOS used to characterize flame acceleration
  - Laminar burning velocities agrees with existing data
  - Critical radius decreases with concentration
  - Fractal excess constant across full range of concentrations studied

- Flame self-acceleration must be considered when modeling lean hydrogen-air flames at large scale
  - Laminar burning velocity alone will significantly under-predict flame speed
Questions?