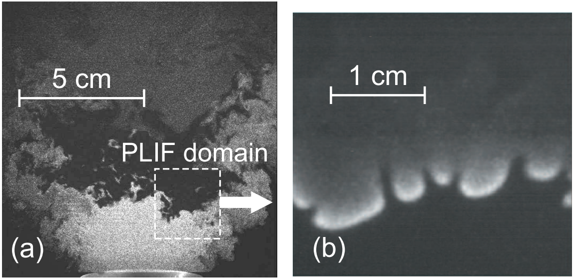
Ultra-Lean Premixed Hydrogen Combustion

J. Bell, M. Day, J. Grcar, M. Lijewski, R. Cheng, I. Shepherd

Lawrence Berkeley National Laboratory

10th Premixed Flame Workshop
Mainz, Germany
August 12-13, 2006

Hydrogen combustion



- OH PLIF shows gaps in the flame
- Flame is not a continuous surface
- Standard flame analysis techniques not applicable

Simulation of ultra-lean premixed hydrogen flames

Focus on central core region

- Little swirl
- Weak net strain

Premixed Flame Simulation Strategy

- Laboratory (requires stabilization mechanism)
  - Swirl
  - Stagnation plate
  - Rod or bluff body
  - Pilot flame or heated wire

- What about computational studies?
  - Simulate a complete laboratory flame (expensive!)
  - Inflow turbulence and let it interact with the flame

Rutland/Trouve (1993)
Zhang/Rutland (1995)
Bell et al. (2002)
Chakraborty/Cant (2004)
Trouve/Poinsot (1994)
Tanahashi, et al (2000,2002)
Cant et al. (2002)

Controlled Flame Simulation

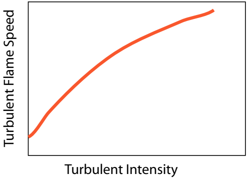
Flame in this configuration is not statistically stationary

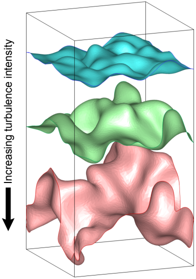
In flamelet regimes, fuel consumption determined primarily by flame surface area

- Inflow too fast, flame drifts up, wrinkles less
- Inflow too slow, drifts down, wrinkles more

Natural flame instability makes this configuration unstable.

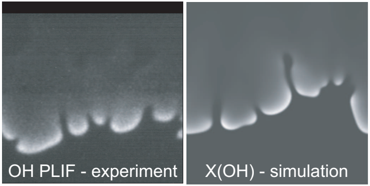
- Use feedback control to stabilize flame
  - Dynamically adjust inflow velocity, v_{in}
  - Require that v_{in} be smooth and positive for numerics
- Simple geometry
- Statistically stationary
- Detailed characterization of turbulent flame behavior

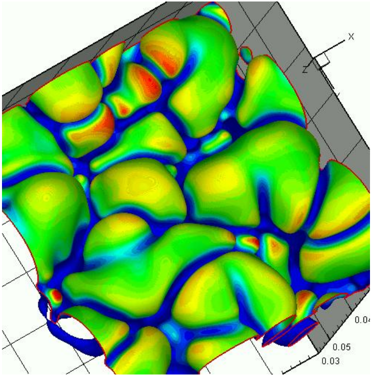




Hydrogen flame in 3D

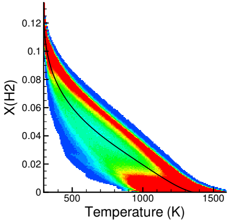
3D control simulation of premixed hydrogen flame at $\phi = 0.37$
($3 \times 3 \times 9$ cm domain, $\Delta x_f = 58\mu$m)

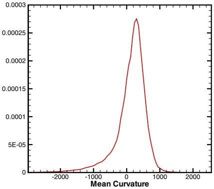


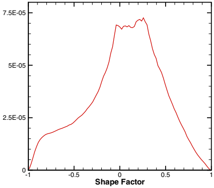


- Figure is “underside” (from fuel side of flame)
- Flame surface (isotherm) colored by local fuel consumption
- Cellular structures convex to fuel, robust extinction ridges

Chemistry in ultra-lean hydrogen flames



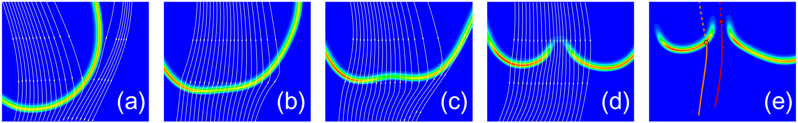




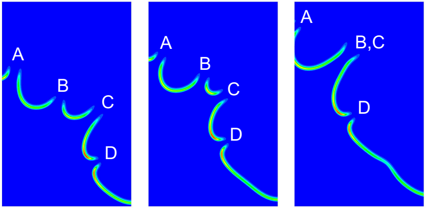
- Significant difference in burning characteristics
- Most burning occurs at conditions substantially different than laminar flame
- Burning occurs at richer conditions
- Fuel diffuses to burning region off of pathlines through extinction gaps

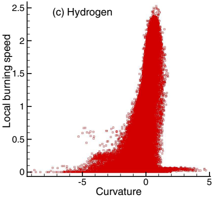
Localized hydrogen flame "extinction"

Analysis from 2D study



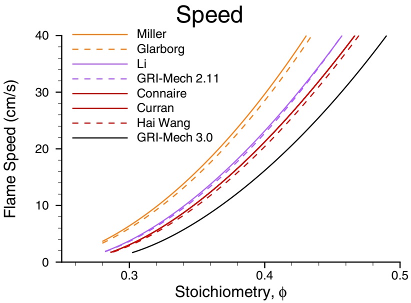
- Low-level localized strain event leads to onset of extinction.
- Lagrangian pathline analysis shows highly mobile fuel atoms diffuse "off-pathline", no fuel leakage.

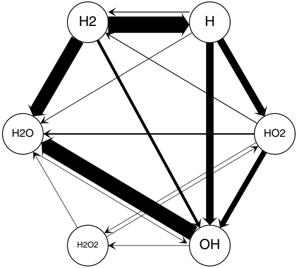


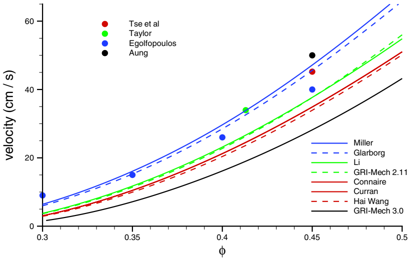


Extinction pockets once formed are very robust

Hydrogen Chemistry at Lean Conditions







One-dimensional flame analysis courtesy of Joe Grcar

Ultra-Lean Hydrogen Issues

- Cellular structure poses issues for experimental data analysis
  - Regions of local extinction separate by regions of intense reaction
  - Extinction regions extremely robust
- Significant chemistry issues at lean conditions
  - What experiments can be done to improve kinetics at lean conditions

How can simulation be most effectively used to help understand ultra-lean hydrogen combustion?

- Relationship between OH PLIF and local consumption speed
- Quantify local flame enrichment
- Better representation of full laboratory experiment
- Other?