Premixed Flames: Propagation Limits and Stability

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Propagation Limits: Overview

- Issues of “stability”
  - when can we get a flame to propagate in a stable and desired manner
    - flammability limits
    - flashback and blowoff
  - how can we make sure a flame can’t propagate
    - flame quenching
  - what does it take to initiate a flame
    - ignition
- Can examine these issues in the context of the principles/models used to characterize flame speed
**Quenching Distance**

- **Observation**
  - for given passage (e.g., cylindrical tube like bunsen burner), if you make diameter less than some critical value, a flame will not propagate through the tube, even if the velocity of the gas in the tube is below the adiabatic flame speed

- **Quenching distance**
  - flame is quenched for \( d < d_q (\text{geometry, fuel, oxid, } \phi, T, p) \)

- Reason: flame speed essentially zero
  - too much loss from flame (energy, radicals) to walls

- Importance: e.g., prevent flame propagating back into feed system or burner

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**Quenching Distance - Analysis**

- Pick simplest geometry, semi-infinite parallel plates

- **Thermal model** - assume quenching limit caused by balance between chemical energy release and energy losses (e.g., conduction)
  - conservative estimate
    \[
    \dot{Q}_{\text{cond}} = \dot{Q}_{\text{chem}} = \dot{m}_f [\Delta h_R] V
    \]

  \[
  - \lambda 2 A_{\text{surf}} \frac{dT}{dx} \bigg|_{\text{wall}} = -\dot{m}_f \Delta h_R A_{\text{surf}} \frac{d_q}{2} \]

  \[
  = \frac{S_L}{2\alpha} (T_2 - T_1) \rho_\ell c_p
  \]

  from \( S_L \) analysis
Quenching Distance - Model

- Simplifying

\[ d_q^2 \approx \frac{\lambda}{\rho c_p S_L^2} \frac{8\alpha}{S_L^2} = \frac{8\alpha^2}{S_L^2} \]

\[ d_q \approx 2\sqrt{2} \frac{\alpha}{S_L^2} = 2\sqrt{2}\delta_f \]

- So the quenching distance is on the order of (and larger than) the flame thickness

- Discussion point
  - why does the flame get quenched when the walls are a few flame thicknesses away

Quenching Distance - Results

- \( d_q (\text{CH}_4, \text{C}_3\text{H}_8, \text{C}_2\text{H}_6) \)
  - 2-2.5mm @ STP in air
  - min. occurs near \( \phi=1 \), but shifted from \( \delta_f \)

- Discussion points
  - \( d_q (\text{H}_2) \approx 0.6 \text{ mm} \)
  - \( d_{q,\text{cylinder}} > d_{q,\text{plates}} \)
  - diluents
    - \( d_q (\text{He}) \text{ vs. } d_q (\text{Ar}) \)
    - \( d_q (\text{CO}_2) \text{ vs. } d_q (\text{Ar}) \)

ref: Turns

\[ d_q \approx 2-3\delta_f \]
Flammability Limits

• Observation
  – only within a range of $\phi$ can one get a flame to be self-propagating
  – example, will flame propagate all the way through tall tube (vertical, large diameter, e.g., 5 cm)
    • slightly different limits for other configurations (e.g., flat flame burner)
  • Essentially $S_L \rightarrow 0$ below some limit: $S_{L\min}$
    – no stable flame exists below some $\phi$ (for other conditions fixed)………why?

• Lean and rich limits ($\phi_{lean,flam}$, $\phi_{rich,flam}$) depend on
  – fuel/ox/diluents, $T_1$, $p$, configuration

• Simple hydrocarbon, air/O$_2$ systems
  – @STP: $\phi_{lean,flam} \sim 0.5$ ; $\phi_{rich,flam} \sim 2$–4 (~1.7 CH$_4$)
    – rich limit varies with $p$
    – lean limit weaker function of $p$
    – surface/geometry issues (tube size, material) more important at lower pressures
Flammability Limits - Losses

- **Controlling processes**
  - tradeoff between losses (e.g., quenching) from flame/reaction zone (thermal conduction, radical diffusion, radiation: gas or soot) and reaction rates

- **Golden Rule** at limit
  $$\frac{\dot{q}^m_{\text{losses}}}{\dot{q}^m_{\text{heat release}}} \approx \frac{1}{Ze}$$

- **Lower** $T_2$ reduces reaction rates
  - reaction rate so low that flame more susceptible to any losses
  - often expressed that $T_2 < T_{ig}$ (but for 1d, no losses would just produce very slow and thick flame)

Flammability Limits – 3-d Effects

- Flammability limits nominally defined for 1-d flame
  - stability of 1-d structure

- Buoyancy issues for flame in “small” tubes

*Upward propagation*
- Buoyancy-induced flame stretch
- Enhanced Losses
- Direction of flame propagation
- Flame front
- Tube walls

*Downward propagation*
- Cooling combustion products near wall cause sinking boundary layer
- Enhanced Losses
- Direction of flame propagation
- Tube walls

*ref: Wang and Ronney (1993)*
Taylor Instability

- 1-d (flat) flame can be an unstable configuration due to buoyancy

Darrieus-Landau Instability

- 1-d flame can also be hydrodynamically "unstable"
  - due to gas expansion
Stability of Flame to Perturbations

- How else can flame respond to perturbations (e.g., local velocity changes)?
- When will perturbations grow or decay?
- For now, consider only thermal conduction:
  - Heat loss decreases $S_L$ for convex bump (into reactants) = neg. stretch
  - Focused heating increases $S_L$ for concave bump (into products) = pos. stretch
  - Always flattens flame, perturbations decay

Thermo-Diffusive Instability

- Now consider reactant diffusion:
  - Deficient reactant will diffuse
    - To convex bulge ⇒ grows perturbation
    - Away for concave bulge ⇒ grow perturbation
  - So perturbations will grow if reactant diffusion outweighs thermal diffusion
    - If $Le < 1$
  - Flames are thermo-diffusively unstable to perturbation for
    - “Light” fuels + leaner mixtures
    - “Heavy” fuels + richer mixtures
Markstein Number Criterion

- In terms of Markstein number
- To be unstable
  - \( S_L < S_L^o \) for negative stretch (\( K_a < 0 \))
  - \( S_L > S_L^o \) for positive stretch (\( K_a > 0 \))
- So unstable when \( M_a < 0 \)

\[
\frac{S_L}{S_L^o} = 1 + M_a K_a
\]

Propane-Air
1 atm

Stable
Unstable

Correlation
\( M_a = -8.8(\phi - 1.44) \)

\( \phi \)

after Tseng et al., Combust. and Flame 95, 410 (1993)

Flame Perturbations

- Must also consider effect on flow (velocity)
  - e.g., convex case - flow diverges
  - centerline velocity will initially decrease (easier for flame to propagate)
Cellular Flames

- $N_2$ diluted flames of heavy hydrocarbons
  - for sufficiently rich $\phi$, flames unstable to perturbations
  - breaks into cellular structure

**Ref:** G. H. Markstein, J. Aero. Sci. 18, 199 (1951)

Flame Extinction by Stretch

- If $\kappa$ is too large, flame temperature and $S_L$ drops
- Eventually leads to extinction at $\kappa_{\text{ext}}$, "extinction strain rate"
  - occurs at $Ka \approx 1$
  - $Ka \sim \tau_{\text{chem}} / \tau_{\text{stretch}}$
  - value may be different for curvature and flow induced stretch

**Ref:** C.K. Law, Combustion Physics

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AE/ME 6766 Combustion
Extinction Strain Rate

- Roughly correlates with inverse of flame time scale
  - higher $S_L$ (φ near 1) leads to higher $k_{ext}$
  - H$_2$ can withstand higher strain than methane

Note: data not obtained at constant flame temperature

CH$_4$/H$_2$ and air

$\alpha = \% \text{ H}_2 \text{ in fuel (vol)}$


Strain Induced Extinction

- Example: (turbulent) flame

Threshold for extinction

Flow Strain on flame

Increase air flowrate

from: T. Lieuwen
Flame Stabilization (Flame Holding)

- **Issue**
  - requirement for flame to remain spatially stable, i.e., stationary
  - normal component of local approach velocity must equal local flame speed
- For combustor, nonstationary behavior leads either to
  - **flashback** \( u_e < S_L \)
    - flame moves upstream (explosion danger, unexpected heating)
  - **blowoff** \( u_e >> S_L \)
    - flame exits combustor or extinguishes

Flame Stabilization: Bunsen Burner

- Consider case of cylindrical tube
  - focus on exit edge
  - \( S_L \) will tend to decrease near wall
  - assume linear \( u \) profile near tube
  - stabilization depends on \( S_L \) vs. \( u \) variation
- So stability of flame for given flame speed depends on burner’s velocity gradient \( \equiv g \)
Critical Gradients

- **Simple model**
  - flame speed constant, drops to zero within penetration depth ($d_p$) of wall
  - linear velocity distribution near wall
    - fully-developed laminar pipe (cyl.) flow, parabolic profile $g = du/dr|_{r=R} = 8\bar{u}/d$

- **Flashback**
  - occurs for $u < S_L$ anywhere at exit
    $$g_f \approx \frac{S_L}{d_p} \approx \frac{S_L}{d_g/3} \approx \frac{S_L}{\delta_f}$$

- **Blowoff**
  - flame can not exist at exit of tube if $u > S_L$ everywhere
    - flame will **liftoff**
  - stability achieved above burner
    - lifted flame can see lower local $u$ (jet expands around wall) $\bar{u}$
    - flame moves farther from wall (reduced quenching, local $S_L$)
  - increasing flowrate increases liftoff until stable configuration impossible ⇒ **blowoff**
    - velocity and dilution
Example: Methane-Air

- For mixtures of CH₄/air @ STP

\[ g_f (s^{-1}) \]

\[ g_b (s^{-1}) \]

\[ g_f \approx S_L/\delta_f \approx S_L/\alpha S_L \propto RR \]

\[ g_{f,b} (s^{-1}) \]

stable

Bunsen Flame Stabilization

- Examine stability constraints (ϕ≈1)

\[ Re_d = \frac{\bar{u} d}{\nu} = 2000 \]

prevent blowoff

\[ \bar{u} = \frac{d}{8} g_f \]

prevent flashback

\[ \bar{u}_f = \frac{d}{8} \frac{S_L}{\delta_f/2} \]

\[ \bar{u} \geq 2S_L \]

to get cone to form

\[ d \]

size for maximum stability range
Multiport Burner Stabilization

- Similar stability diagram for multiple premixed fuel/air ports (single row)
- Rich mixtures more stable
  - unburned fuel
  - soot emissions

Flame Stabilization: General

- As illustrated in the laminar Bunsen flame example:
  1. stationary premixed flames controlled by flame propagation are generally stabilized by one or more “anchor” locations
    - anchoring typically occurs at “upstream” location
    - flame position downstream of anchor (for continuous flame) is determined by local flame angle history
Flame Stabilization: General

2. previously we considered flame stabilization anchor occurring at a location where the local flame speed matches the local flow velocity (normal flame stabilization)
   – other options possible, e.g., edge flame stabilization
     • divergence of oncoming reactants around upstream flame edge reduces local velocity
     • may be important in turbulent jet flames, shear layer stabilized flames

Flame Stabilization: General

3. stability is improved by providing either regions of
   – sufficiently low velocity or
   – sufficiently high flame speed
   – or in terms of flow time and chemical time, high Damköhler number
Flame Stabilization: General

• Common approaches to reduce local flow velocity (or increase residence time)

  1. **bluff bodies**: low velocity wake

  2. **sudden expansion (dump)**: rapid expansion

  3. **swirl**: aerodynamically induced recirculation zone

• Common approaches to increase flame speed (or decrease chemical time)

  1. **optimize equivalence ratio**: rich pilot for lean mixture

  2. **raise reactant temperature**: preheat, exhaust gas recirculation (EGR)

  3. **raise pressure**

  4. **reduce heat losses**: near stabilization region

  5. **modify fuel**: add H₂