Nonpremixed Combustion

- Most common form employed in high power and industrial (especially liquid fueled) combustors
  - reactants entering combustor initially nonpremixed
  - simpler (no requirement to prevaporize/mix reactants)
  - easier to control flame stability

Yuan et al., Intl J Spray & Comb Dynamics 2018
(diesel) energy.gov
(flare) generon.com

Process Heating
Nonpremixed Combustion

• Engineering issues
  – flame shape, size, location (combustor length, …)
  – flame stability (liftoff, blowout, …)
  – heat transfer (radiation-soot, distance to walls, …)
  – pollutant emissions (NOₓ, UCH/CO, …)

  Process Heating
  
  Yuan et al., Intl J Spray & Comb Dynamics 2018
  
  (diesel)
  
  energy.gov
  
  (flare) generon.com
  
  AE/ME 6766 Combustion

Nonpremixed Combustion

• Combustion science issues
  – local mixing (fuel, oxidizer, hot products, …)
    • scalar dissipation, turbulent transport, partial premixing, differential diffusion
  – highly nonlinear dependence of reaction rates on T, Y₁,…
  – density/buoyancy, flow instabilities

  Process Heating
  
  Yuan et al., Intl J Spray & Comb Dynamics 2018
  
  (diesel)
  
  energy.gov
  
  (flare) generon.com
  
  AE/ME 6766 Combustion
**Common Burner Configurations**

- Typical to use fuel jets flowing into
  - quiescent oxidizer (air) “jet flame”
  - coaxial oxidizer jet
  - swirled coaxial oxidizer

- Though many other configurations exist
  - impinging jets, jets-in-crossflow,…

---

**Nonpremixed Jet Flames**

- **Flame Length Example**

\[
L_f = \frac{d}{2} = R_e
\]

\[
Q_e = \dot{m} u R_e^2 \quad (cm^3/s)
\]
Flame Length Relations

- Empirical relations available for flame lengths of turbulent jet flames (Kalghati)

\[
L_f = L' \frac{d_x}{f_{stoich}} \left( \frac{\rho_e}{\rho_\infty} \right)^{1/2} 
\]

\[(X.10) \quad L_f \propto u_x d_x^{3/2} \times f_{stoich} \left( \frac{\rho_e}{\rho_\infty}, \frac{\rho_{flame}}{\rho_\infty} \right)\]

\[
L' = \begin{cases} 
13.5 Fr_f^{2/5} & \text{Fr}_f < 5 \quad \text{buoyancy effected} \\
23 & \text{Fr}_f \geq 5 \quad \text{momentum dominated}
\end{cases}
\]

- flame Froude number

\[
Fr_f = \left( \frac{\rho_e}{\rho_\infty} \right)^{1/4} \frac{u_x f_{stoich}^{3/2}}{gd_x (T_f - T_a)^{1/2}}
\]

Nonpremixed Jet Flames

- Flame structure
  - based on visual and photographic observations
Nonpremixed Jet Flames

• Instantaneous flame structure
  – from laser sheet imaging
  – reaction zone relatively thin and highly wrinkled
  – structure sizes and high temperature regions larger as we go downstream

from Ö. Gülder

Nonpremixed Jet Flames

• Can observe localized breaks in flame front
  – localized extinction
  – can grow: larger region of extinction
  – can shrink: neighboring flames propagate into unburned reactants
Nonpremixed Flame Regimes

- Repeating regime diagram based on (X.3)

\[ Ka \approx Da_e / Re_{\ell_o}^{1/2} \]

\[ Ka = Da_k^{-1} \]

- Flamelets
  \[ Ka = 0.01 \]
  \[ Da_e \]

- Broken Flamelets
  \[ Ka = 1 \]
  \[ Re_{\ell_o} \]

- Distributed Reaction Zones
  \[ Ka = 100 \]
  \[ Re_{\ell_o} \]

Fast Chemistry Approaches

- For high \( Da_e \) and low \( Re_{\ell_o} \) (\( Ka \leq 1 \)) can assume chemistry is much faster than all turbulent scales
  - Local chemical equilibrium or flame sheet approximation
  - Can relate species concentrations and temperature to mixture fraction
  - Conservation/transport equation for \( f \)
    \[
    \frac{\partial}{\partial t} (\rho f) + \nabla \cdot (\rho \vec{u} f) - \nabla \cdot (\rho D \nabla f) = 0
    \]
    Unsteady term
  - With \( Le = 1 \) and no heat losses (no radiation or nearby surfaces), can rely on state relations
Equilibrium State Relations

- Example, for $Le=1$ (H$_2$-air)

![Graph showing Mixing Lines](no reaction)

$T_f = T_{av} = 300 K, p = 1 \text{ atm}$

- Nonpremixed jet flames of different exit velocity
  (Raman scattering for $f$; Rayleigh scattering for $T$)

- high $Da$ ($u_e = U$)
  - near equil. results
  - each point represents instantaneous measurement at same point in the flowfield

- lower $Da$ ($u_e = 3U$)
  - finite rate (slow) chemistry effects

- large fluctuation in $f$ at fixed point

Magre and Dibble, Combustion and Flame 73, 195 (1988)
**CH₄-Air Experiments**

- Jet flame with slower chemistry; comparison to oppdif
  - \( u_c = 48 \text{m/s}, D = 7.2 \text{mm} \)
  - \( \kappa = 1 \text{s}^{-1} \)
  - \( x/D = 10 \)
  - usually near fast chem. result
  - \( x/D = 20 \)
  - slow chemistry, local extinction evident

Masti *et al.*, Combustion and Flame 73, 261 (1988)

**Transport of \( f \)**

- Common engineering solution
  - only solve for time-averaged \( f \)
  
  \[
  \nabla \cdot \left( \rho \bar{u} \bar{f} \right) - \nabla \cdot \left( \rho \bar{u}'' \bar{f}'' \right) - \rho D \nabla \bar{f} = 0
  \]

  - \( \bar{f} = \) time average \( = \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_0^{\Delta t} f(\bar{x}, t) dt \)
  - \( \bar{f} = \) Favre average \( = \rho \bar{f} / \rho \) density weighted
  - \( \bar{f}'' = \) Favre fluctuation \( f = \bar{f} + f'' \)

  - If molec. diff. term negligible, Gradient Transport Model
    
    \[
    \nabla \cdot \left( \rho \bar{u} \bar{f} \right) = \nabla \cdot \left( \rho \bar{u}'' \bar{f}'' \right) \\
    \left( \rho \bar{u}'' \bar{f}'' \right) \approx -\rho \nabla \cdot \nabla \bar{f}
    \]

    eddy diffusivity – e.g., from k-ε model
Finite Rate Chemistry

• Flamelet models
  – instead of using fast chemistry assumption, can parameterize $f \rightarrow T, Y_i$ relations by using local scalar dissipation rate, $\chi$
    \[ \bar{\chi} = 2 \rho D (\nabla f'^n)^2 / \rho \]
  – try to characterize turbulent nonpremixed flame as ensemble of laminar nonpremixed flamelets

Flamelet Approach

• So relate scalars ($f$) to strained nonpremixed laminar flamelet calculations (instead of equilibrium)
  \[ \chi = \chi(a) \quad \text{strain rate} \]
  – try to characterize turbulent nonpremixed flame as ensemble of laminar nonpremixed flamelets

\[ Y_i = Y_i^{(F)}(f) \Rightarrow \nabla Y_i = \frac{\partial Y_i^{(F)}}{\partial f} \nabla f \]

\[ \frac{\partial}{\partial t} \left( \rho Y_i \right) + \nabla \cdot \left( \rho \bar{u} Y_i \right) - \nabla \cdot \left( \rho D \nabla Y_i \right) = \dot{m}_m^{(R)} \]

\[ \frac{\partial}{\partial f} \left[ \frac{\partial}{\partial t} (f'Y_i^{(F)}) + \nabla \cdot (\rho \bar{u} f Y_i^{(F)}) - \nabla \cdot (\rho D \nabla Y_i^{(F)}) \right] - \rho D \left( \nabla f \right)^2 \frac{\partial^2 Y_i^{(F)}}{\partial f^2} = \dot{m}_m^{(R)} \]
Flamelet Approach

- Flamelet equation
  \[- \rho D (\nabla f)^2 \frac{\partial^2 Y_i^{(f)}}{\partial f^2} = \bar{m}_i^{\prime \prime}\]
  - to get average chemical species formation/destruction
  - need average flamelet equation
  - one approach: probability distributions (PDFs) of \( f \)

\[
\bar{m}_i^{\prime \prime} = -\frac{1}{2} \rho \left[ \int_{0}^{\chi} \chi \frac{\partial^2 Y_i^{(f)}}{\partial f^2} \tilde{P}(\chi, f) d\chi df \right]
\]

Favre-avg. Joint PDF

from laminar experiments or calculations (on-line or library)

shape = ?