Introduction to Turbulent Combustion: Turbulent Premixed Flames

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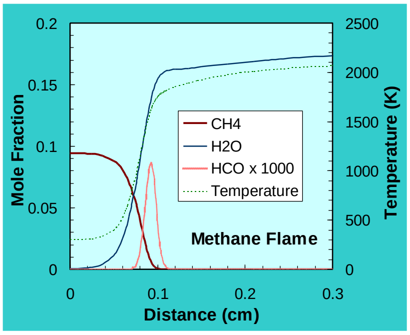
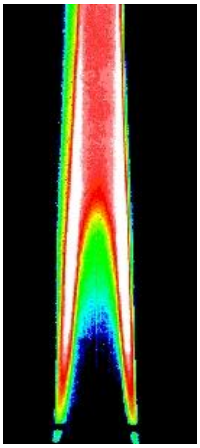




Overview

- The specific goals of this section:
  1. Refine combustion regime paradigm for turbulent premixed systems by comparing to laminar flame scales
     - Borghi-Peters diagram
  2. Introduce turbulent flame speed S_T
  3. Examine simple models for S_T scaling (e.g., vs. S_L)
  4. Comments on local extinction and turbulent combustion modeling based on G equation

Length and Velocity Ratios

- Compare turbulent to laminar premixed scales
- **Length scale ratio**
  - – start by comparing turbulent macroscale to a characteristic premixed flame dimension
    - laminar (unstretched) flame thickness

$$\frac{\ell_o}{\delta_{f_L}} \approx \frac{\ell_o}{\alpha / S_L^o} \approx \frac{\ell_o}{\sqrt{\alpha \tau_{chem}}} \approx \frac{\ell_o}{\sqrt{\nu \tau_{chem}}}$$

assuming *Pr*~1, so ν~α

$$\frac{\ell_o}{\delta_{f_L}} \approx \left(\frac{\ell_o / \sqrt{2q}}{\tau_{chem}} \frac{\ell_o \sqrt{2q}}{\nu} \right)^{1/2}$$

$$\frac{\ell_o}{\delta_{f_L}} \approx \left(Da_\ell \operatorname{Re}_{\ell o} \right)^{1/2} \quad \text{(X.4)}$$

Length and Velocity Ratios

- **Velocity ratios**
  - – now compare rms turbulent velocity fluctuation to laminar flame speed

$$\frac{u'_{rms}}{S_L^o} = \frac{\sqrt{2q}}{S_L^o} \approx \frac{\sqrt{2q}}{\sqrt{\nu / \tau_{chem}}}$$

again for *Pr*~1

$$\approx \left(\frac{\sqrt{2q}}{\nu} \sqrt{2q}\, \tau_{chem} \right)^{1/2} = \left(\frac{\sqrt{2q}\,\ell_o}{\nu} \frac{\sqrt{2q}}{\ell_o} \tau_{chem} \right)^{1/2}$$

$$\left. \begin{aligned} \frac{u'_{rms}}{S_L^o} &\approx \left(\operatorname{Re}_{\ell o} / Da_\ell \right)^{1/2} \\ \frac{\ell_o}{\delta_{f_L}} &\approx \left(Da_\ell \operatorname{Re}_{\ell o} \right)^{1/2} \end{aligned} \right\} \Rightarrow$$

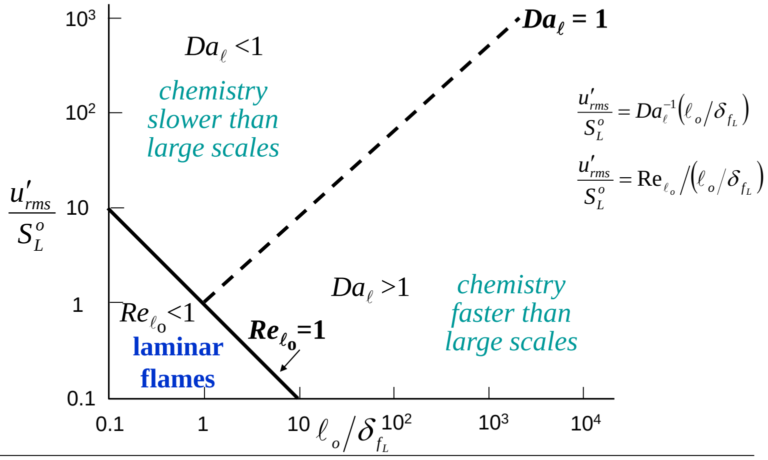
recall (X.4)

$$\boxed{\frac{u'_{rms}}{S_L^o} = Da_\ell^{-1} \left(\ell_o / \delta_{f_L} \right)} \quad \text{(X.5)}$$

$$\boxed{\frac{u'_{rms}}{S_L^o} = \operatorname{Re}_{\ell_o} / \left(\ell_o / \delta_{f_L} \right)} \quad \text{(X.6)}$$

Length and Velocity Ratios

- Graphically representing these relationships



$$\frac{u'_{rms}}{S_L^o} = Da_\ell^{-1}\left(\ell_o/\delta_{f_L}\right)$$

$$\frac{u'_{rms}}{S_L^o} = \mathrm{Re}_{\ell_o}/\left(\ell_o/\delta_{f_L}\right)$$

Small Scales and Karlovitz Number

- Above length and velocity ratios are for large scale turbulent structures
- What about small scales, i.e., ℓ_k vs. δ_{fL} ?
  - previously saw $\ell_k = \ell_o Re_{\ell_o}^{-3/4} \Rightarrow \ell_k/\delta_{fL} = (\ell_o/\delta_{fL})\, Re_{\ell_o}^{-3/4}$
  - using (X.4) $\ell_k/\delta_{fL} = (Da_\ell\, Re_{\ell_o})^{1/2} Re_{\ell_o}^{-3/4}$
    $\ell_o/\delta_{f_L} \approx \left(Da_\ell\, \mathrm{Re}_{\ell_o}\right)^{1/2}$ $\quad = (Da_\ell\, Re_{\ell_o}^{-1/2})^{1/2}$
  - but from (X.3) $Da_\ell \approx \mathrm{Re}_{\ell_o}^{1/2} Da_k$ $\Rightarrow \ell_k/\delta_{f_L} \approx Da_k^{1/2} = \underbrace{\left(\dfrac{\tau_k}{\delta_{f_L}/S_L^o}\right)^{1/2}}_{\equiv 1/Ka_L}$ $\dfrac{\textbf{Kolmogorov eddy time}}{\textbf{laminar flame transit time}}$
  - **flame turbulent Karlovitz #**

$$\boxed{\ell_k/\delta_{f_L} \approx Ka_L^{-1/2}} \quad \text{(X.7)}$$

@ $Ka_L=1 \Rightarrow \ell_k=\delta_{fL}$
$Ka_L>1 \Rightarrow \ell_k<\delta_{fL}$

Karlovitz Number (con't)

- Velocity ratio?
  - from (X.5) and (X.3)

$$\frac{u'_{rms}}{S_L^o} = Da_\ell^{-1}\frac{\ell_o}{\delta_{f_L}} \qquad Da_\ell \approx \mathrm{Re}_{\ell_o}^{1/2}\, Da_k$$

$$\frac{u'_{rms}}{S_L} \approx \left(Da_k^{-1}\,\mathrm{Re}_{\ell_o}^{-1/2}\right)\frac{\ell_o}{\delta_{f_L}}$$

$$\approx Ka_L\,\mathrm{Re}_{\ell_o}^{-1/2}\,\frac{\ell_o}{\delta_{f_L}}$$

  - from (X.6)

$$\mathrm{Re}_{\ell_o} = \left(u'_{rms}/S_L^o\right)\left(\ell_o/\delta_{f_L}\right)$$

$$\frac{u'_{rms}}{S_L^o} \approx Ka_L\left[\frac{u'_{rms}}{S_L^o}\,\frac{\ell_o}{\delta_{f_L}}\right]^{-1/2}\frac{\ell_o}{\delta_{f_L}}$$

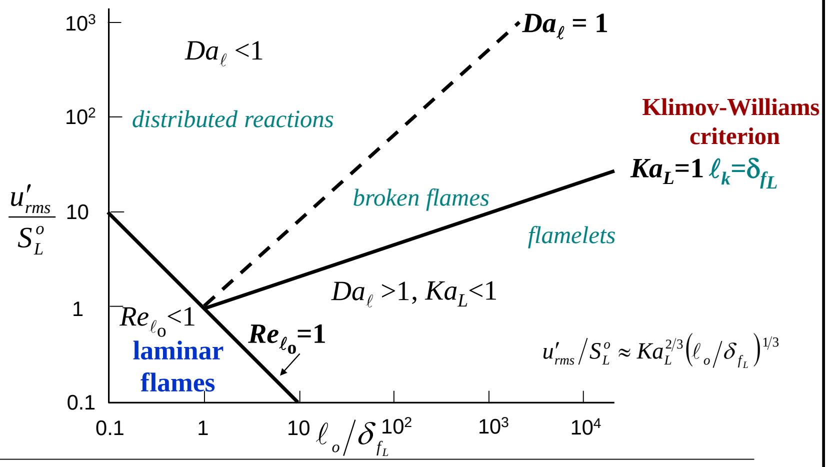
$$\left(u'_{rms}/S_L^o\right)^{3/2} \approx Ka_L\left(\ell_o/\delta_{f_L}\right)^{1/2}$$

Ka_L scaling for velocity and length ratios

$$\boxed{u'_{rms}/S_L^o \approx Ka_L^{2/3}\left(\ell_o/\delta_{f_L}\right)^{1/3}} \quad \text{(X.8)}$$

Karlovitz Scaling

- Add these relations to graph



Reaction Zone Ka

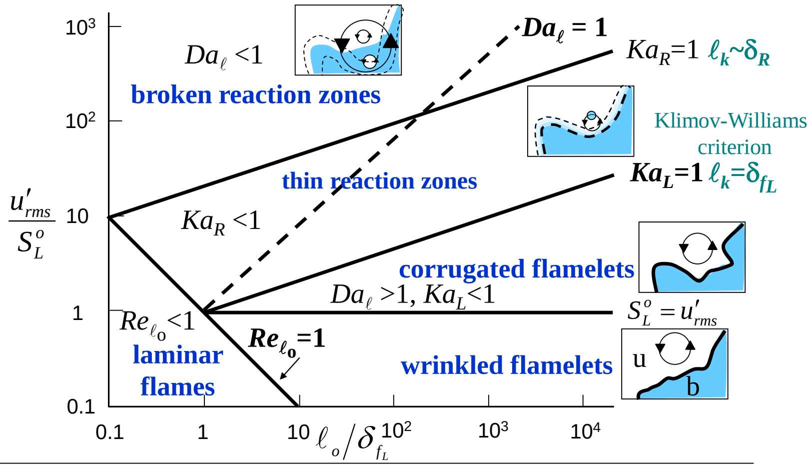
- Can define a second Karlovitz number based on the "reaction zone" thickness δ_R
  - instead of the larger flame thickness δ_{f_L}
  - recall $\delta_R / \delta_{f_L} \sim 1/Ze$, Zelodvich number
- So with (X.7) $Ka_L \approx (\delta_{f_L}/\ell_k)^2$

$$\boxed{\frac{Ka_R}{Ka_L} = \left(\delta_R/\delta_{f_L}\right)^2 = Ze^{-2}} \quad \text{(X.9)}$$

- Recall for many room temperature, HC-air flames, $Ze \sim 10$
  - Ka_R=1 when $Ka_L \sim 100$

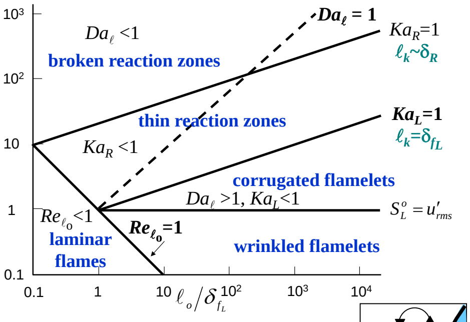
Borghi-Peters Diagram

- Scalings used to differentiate premixed flame regimes

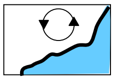


Premixed Flame Regimes

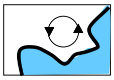
- **Flamelets**
  - all turbulent scales larger than flame thickness
  - turbulent flame acts like distorted laminar flame



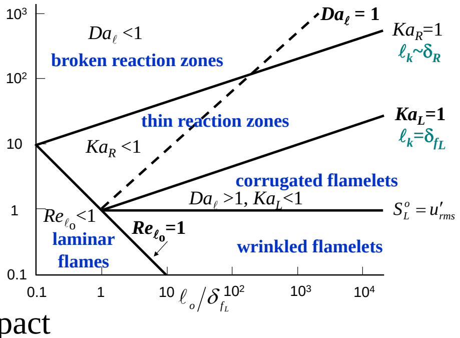
- **Wrinkled Flamelets**
  - $u'_{rms} < S^o_L$
  - *laminar flame propagation dominates turbulent displacement*, i.e., any corrugations in flame front being induced by turbulence

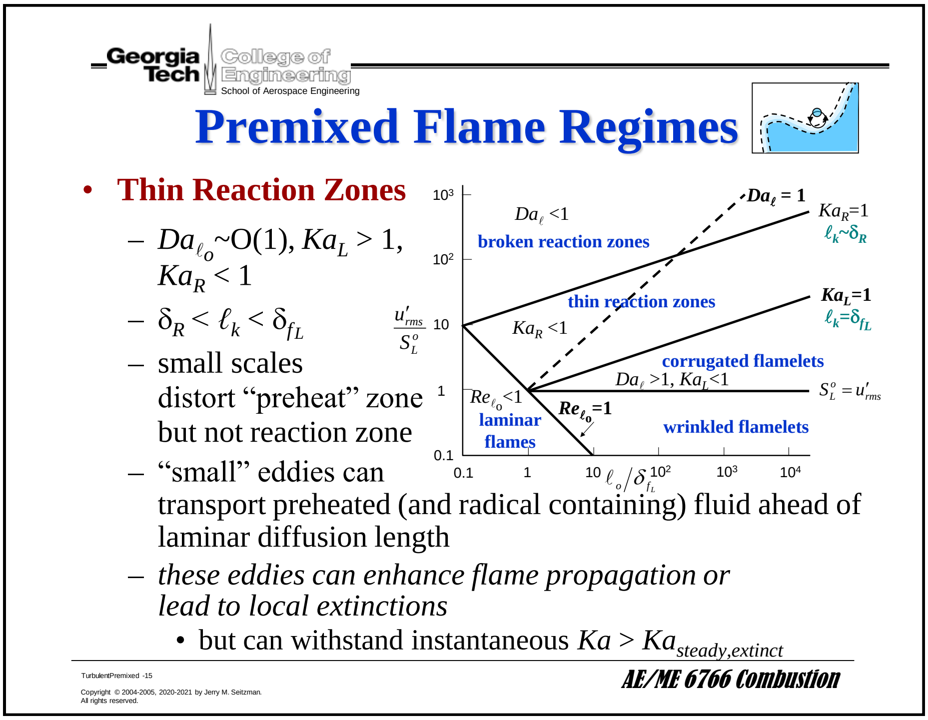


Premixed Flame Regimes



- **Corrugated Flamelets**
  - $u'_{rms} > S^o_L > u'_k$
  - large eddies push flame, cause significant corrugation
  - small eddies too slow and large to impact (internal) flame structure
  - *flame structure remains same as quasi-steady (but stretched) laminar flame*





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Premixed Flame Regimes

- **Thin Reaction Zones**
  - Da_{ℓ_o}~O(1), $Ka_L > 1$, $Ka_R < 1$
  - $\delta_R < \ell_k < \delta_{fL}$
  - small scales distort "preheat" zone but not reaction zone
  - "small" eddies can transport preheated (and radical containing) fluid ahead of laminar diffusion length
  - *these eddies can enhance flame propagation or lead to local extinctions*
    - but can withstand instantaneous $Ka > Ka_{steady,extinct}$

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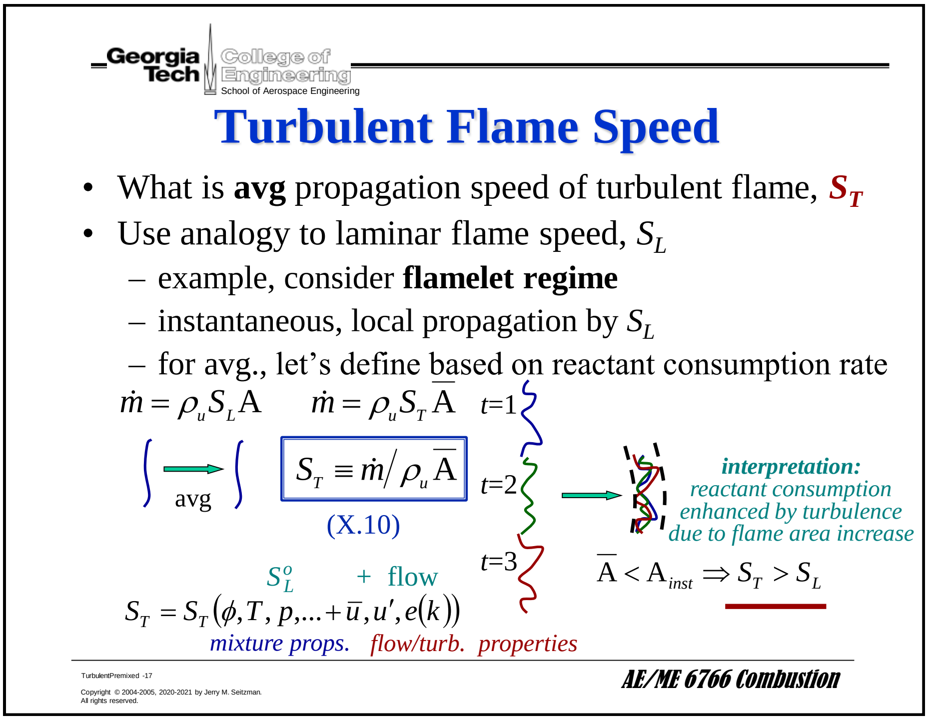
AE/ME 6766 Combustion



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Turbulent Flame Speed

- What is **avg** propagation speed of turbulent flame, S_T
- Use analogy to laminar flame speed, S_L
  - example, consider **flamelet regime**
  - instantaneous, local propagation by S_L
  - for avg., let's define based on reactant consumption rate

$\dot{m} = \rho_u S_L A$ $\quad$ $\dot{m} = \rho_u S_T \bar{A}$

$$\boxed{S_T \equiv \dot{m} / \rho_u \bar{A}}$$

(X.10)

interpretation:
reactant consumption enhanced by turbulence due to flame area increase

$\bar{A} < A_{inst} \Rightarrow S_T > S_L$

$$S_T = S_T(\underbrace{\phi, T, p, \ldots}_{S_L^o} + \underbrace{\bar{u}, u', e(k)}_{\text{flow}})$$

mixture props. *flow/turb. properties*

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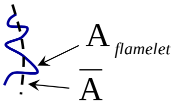
AE/ME 6766 Combustion

S_T for Flamelet Regime

- If instantaneous propagation same as laminar flamelets $$\frac{S_T}{S_L} = \frac{A_{flamelets}}{\overline{A}}$$



- S_L not necessarily constant
  - local flow properties may vary, e.g, T
  - turbulence leads to stretch, $S_L \neq S_L^o$
- Simplest model: no S_L change (flame only “pushed”)
- Damköhler suggested wrinkling related to u'_{rms}

$$\frac{A_{flamelets}}{\overline{A}} \sim 1 + \frac{u'_{rms}}{S_L} \Rightarrow \frac{S_T}{S_L} \cong 1 + \frac{u'_{rms}}{S_L} \Longrightarrow S_T/S_L = \mathrm{f}(\mathrm{Re})$$

Damköhler suggested $\mathrm{Re}^{1/2}$

S_T for Flamelet Regime

- Other models with similar approach

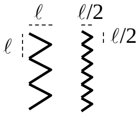
(X.11) $$\boxed{\frac{S_T}{S_L} \cong 1 + \left(\frac{u'_{rms}}{S_L}\right)^n}$$

with $n = n\left(u'_{rms}/S_L\right)$

e.g. $n > 1$ for small u'_{rms}/S_L

$n < 1$ for large u'_{rms}/S_L

  - compare reasonably well with experiments in flamelet regime (especially closer to wrinkled)
  - e.g., SI engines: u'_{rms} scales with RPM (piston velocity) $\Rightarrow$ can burn faster at higher RPM
  - also, length scales not important

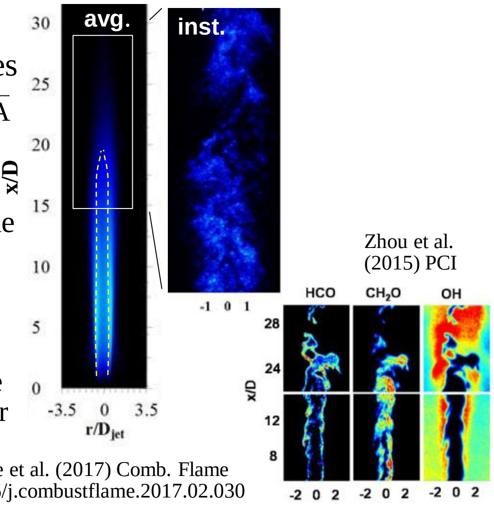


same A

- Models fail as $S_L \rightarrow 0$ (e.g., due to flammability limits,quenching); predicts non-zero $S_T \rightarrow u'_{rms}$

Example: S_T for Turbulent Jets

- Can measure S_T for using various approaches based on X.10 $S_T \equiv \dot{m} / \rho_u \overline{\mathrm{A}}$
  - key is measuring average flame area
  - mean location in flame "brush"
    - center of average luminosity
    - maximum probability of flame location from planar laser imaging

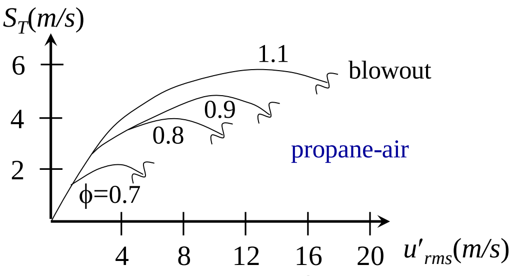


Zhou et al. (2015) PCI

Carbone et al. (2017) Comb. Flame 10.1016/j.combustflame.2017.02.030

Example: S_T for Turbulent Jets

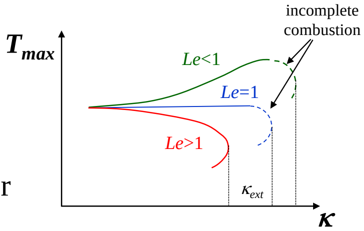
- Turbulent flame speed initially increases with turbulence (u'_{rms})
- S_T also increases with S_L (ϕ here)
- S_T goes through maximum at high u'_{rms} / S_L
- **Why maximum?**
  - $S_L \neq$constant: stretch changes local laminar flamelets; high stretch can lead to extinction



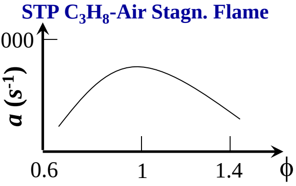
after Abdel-Gayed et al., 20th Comb. Symp (1984)

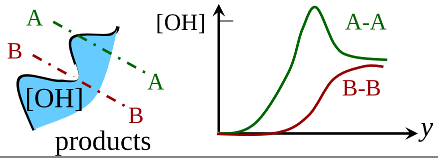
Stretch and Flame Extinction

- Recall stretch can enhance or weaken laminar flames
- Turbulence enhances stretch (and scalar dissipation)
  - ⇒produces higher gradients (higher diffusive fluxes, lower τ_{res})
  - ⇒eventually extinguish flamelet
- Example evidence of local extinction measured with PLIF



Extinction Strain Rate for Laminar STP C_3H_8-Air Stagn. Flame





reduced radical overshoot as approach extinction