A Distinctive Feature of Turbulent Combustion of Lean Hydrogen-Air Mixtures

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Contents of the Lecture

- Background
  - ✓ *Laminar premixed flame*
  - ✓ *Turbulence*
  - ✓ *The major physical mechanism of premixed turbulent combustion*
- Experimental data on turbulent burning velocity
  - ✓ *Ordinary hydrocarbon-air mixtures*
  - ✓ *Lean hydrogen-air mixtures*
- Why does molecular transport substantially affect turbulent combustion at high Reynolds number?

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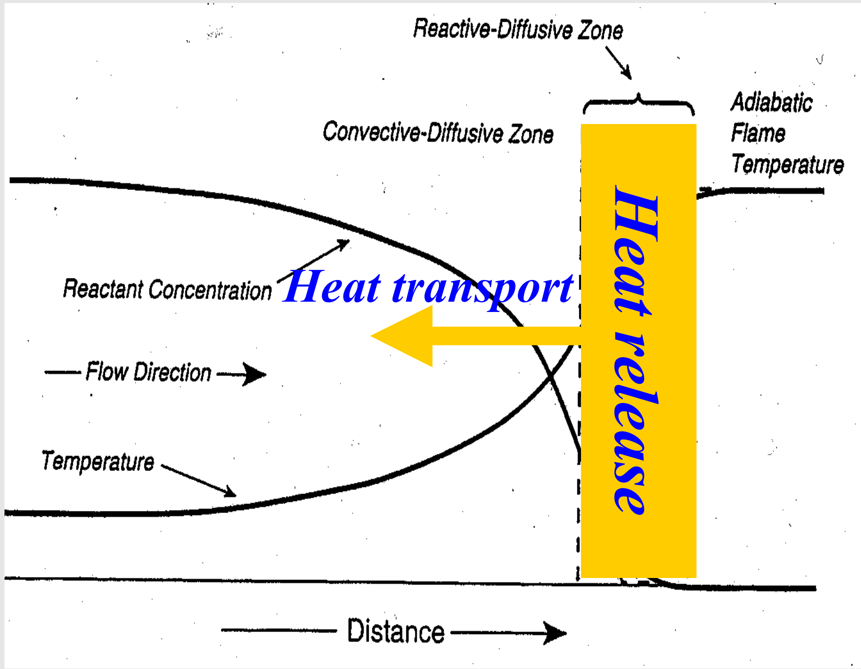
The Physical Mechanism of Flame Propagation in Premixed Reactants

$$\frac{\partial}{\partial t}(\rho Y_k)+\frac{\partial}{\partial x_j}(\rho u_j Y_k)=\boxed{-\frac{\partial J_{kj}}{\partial x_j}}+\boxed{\rho w_j}$$

$$\frac{\partial}{\partial t}(\rho T)+\frac{\partial}{\partial x_j}(\rho u_j T)=\boxed{-\frac{\partial J_{Tj}}{\partial x_j}}+\boxed{\rho w_T}$$

Molecular transport:

$$\boxed{J_{kj}=-\rho D_k\frac{\partial Y_k}{\partial x_j};\quad J_{Tj}=-\rho\kappa\frac{\partial T}{\partial x_j}}$$



From the paper by Williams, F.A., "Progress in knowledge of flamelet structure and extinction," Progress in Energy and Combustion Science 26: 657-682 (2000).

Chemical Reactions:

$$\boxed{w_j \propto \frac{1}{t_r}\exp\left(-\frac{\Theta_j}{T}\right)}$$

Flame propagation in premixed reactants is caused by

the heat release in chemical reactions

and

the molecular transport of the heat into the unburned mixture.

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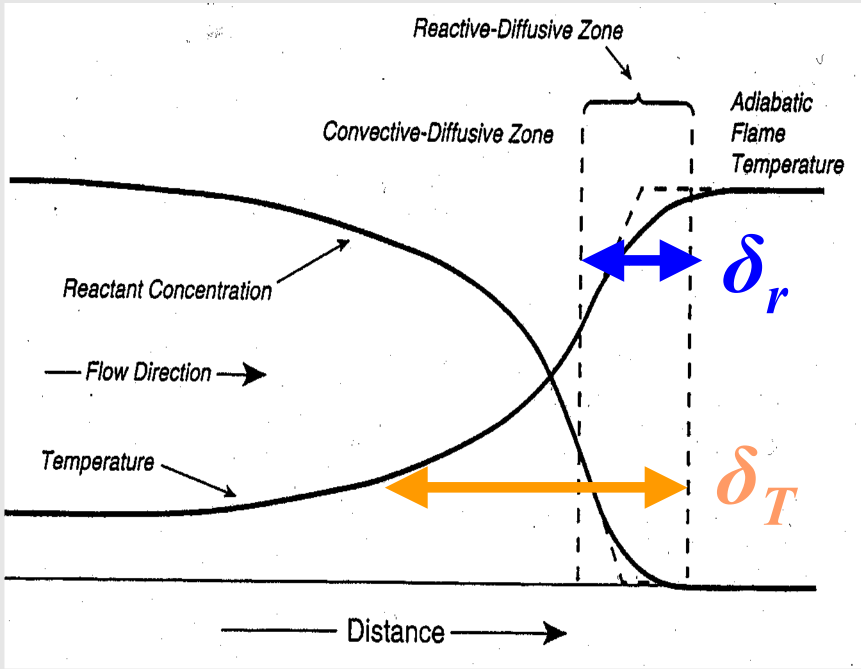

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Chemical Reactions:

$$\boxed{w_j \propto \frac{1}{t_r}\exp\left(-\frac{\Theta_j}{T}\right)}$$

$$\Theta \approx 20\ 000^{o}\ \mathrm{K}$$

The key peculiarity of premixed combustion is as follows:

major chemical reactions that control the heat release are confined to very thin reaction zone!

Typical Values of Laminar Flame Speed and Thickness

$$S_L \propto \sqrt{\kappa_u w_{Tm}}$$

$$\delta_L \propto \sqrt{\frac{\kappa_u}{w_{Tm}}} \propto \frac{\kappa_u}{S_L}$$

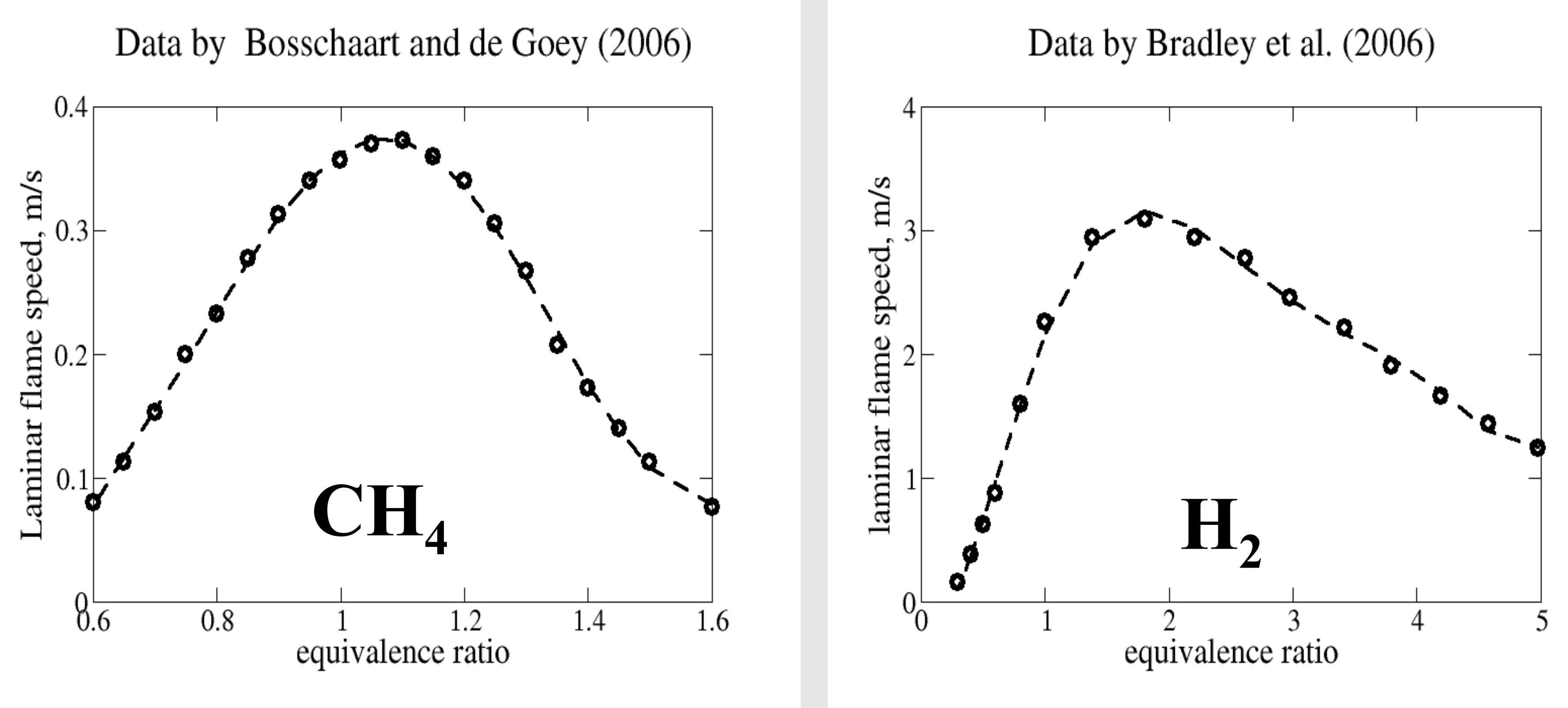
Hydrocarbon-air flames:

- $S_L \approx 0.4$ m/s
- $\kappa_u \approx 0.02$ cm^2/s
- $\delta_r \approx 0.05$ mm
- $\delta_T \approx 0.5$ mm

Hydrogen-air flames:

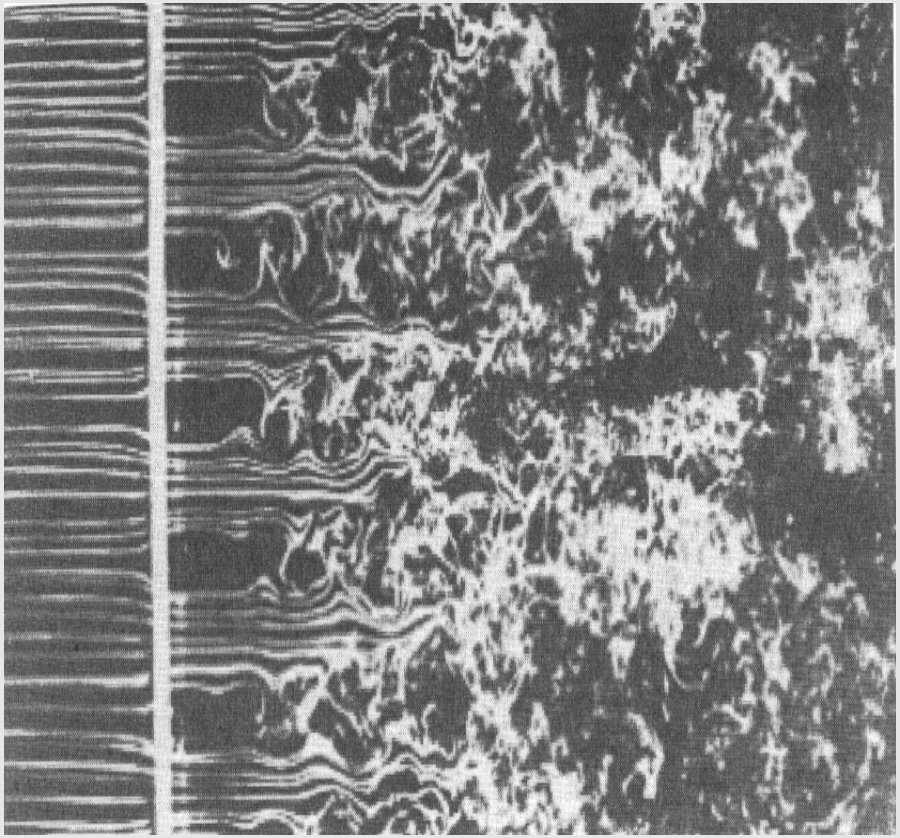
- $S_L \approx 2$ m/s
- $\kappa_u \approx 0.05$ cm^2/s
- $\delta_r \approx 0.02$ mm
- $\delta_T \approx 0.2$ mm

Laminar Flame Speed

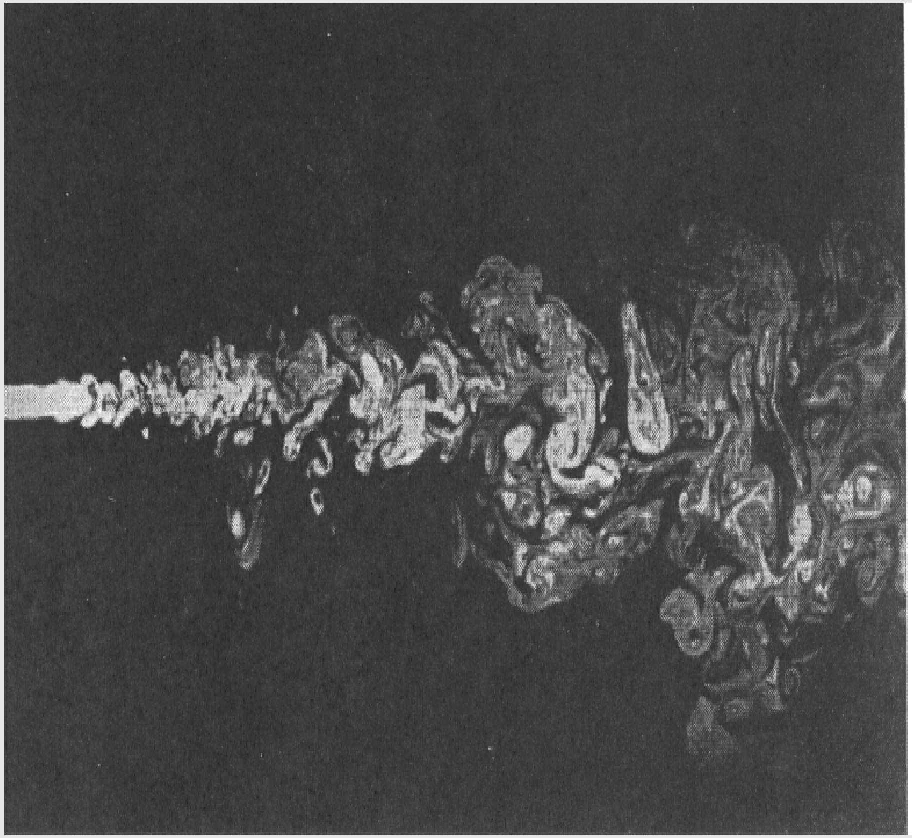


$$F = \frac{Y_F}{Y_{F,St}}$$

Turbulent Flows



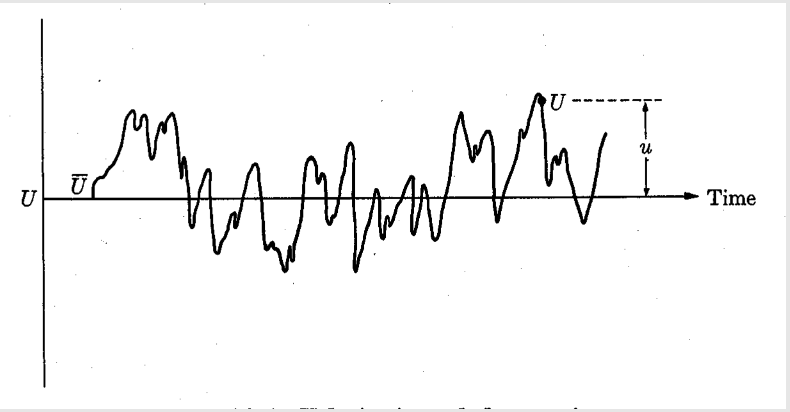
Photograph by Corke & Nagib



Photograph by Dimotakis et al.

Main Characteristics of Turbulence

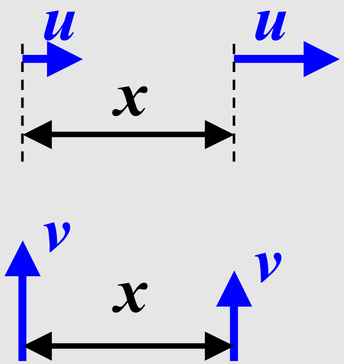
rms turbulent velocity



$$U(\mathbf{x}) = \overline{u}(\mathbf{x},t) = \frac{1}{\tau}\int_{t}^{t+\tau} u(\mathbf{x},\eta)\,d\eta$$

$$u' = \left\{\frac{1}{\tau}\int_{t}^{t+\tau}\left[u(\mathbf{x},\eta) - \overline{u}(\mathbf{x})\right]^2 d\eta\right\}^{1/2}$$

Integral length scale

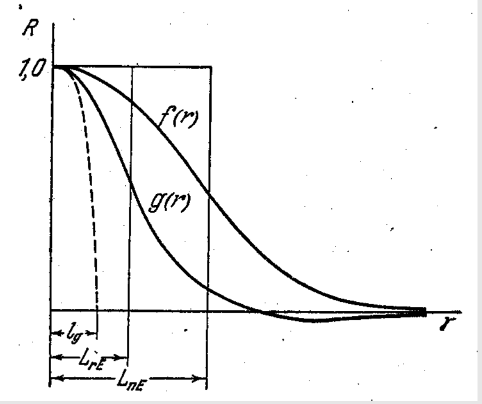


$$f(x) = \frac{\overline{u'(x_0)u'(x_0+x)}}{u'(x_0)u'(x_0+x)}$$

$$g(x) = \frac{\overline{v'(x_0)v'(x_0+x)}}{v'(x_0)v'(x_0+x)}$$

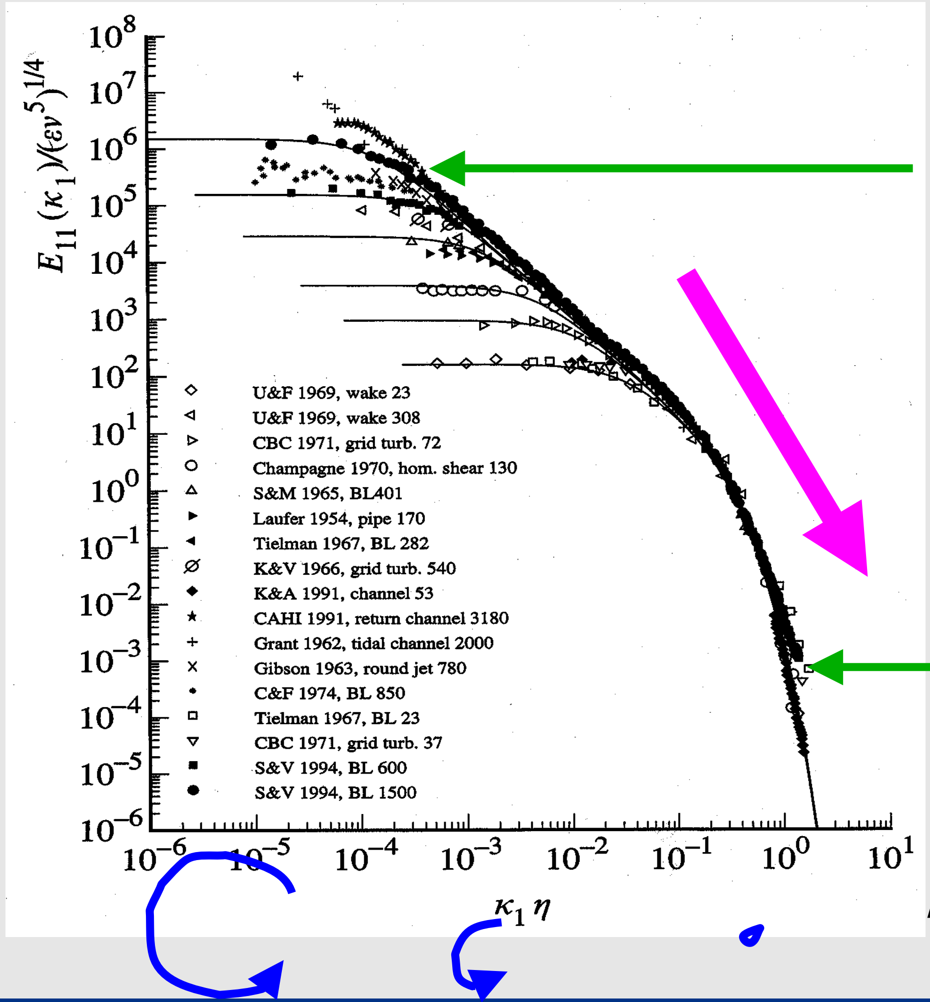
$$L_{E\parallel} = \int_0^\infty f(x)\,dx$$

$$L_{E\perp} = \int_0^\infty g(x)\,dx$$



Turbulence Spectrum

From the book by S.B. Pope "Turbulent Flows",
Cambridge University Press, Cambridge, UK, 2000.



$$\varepsilon \propto \frac{u'^3}{L}$$

$$\mathrm{Re}_t = \frac{u'L}{\nu} >> 1$$

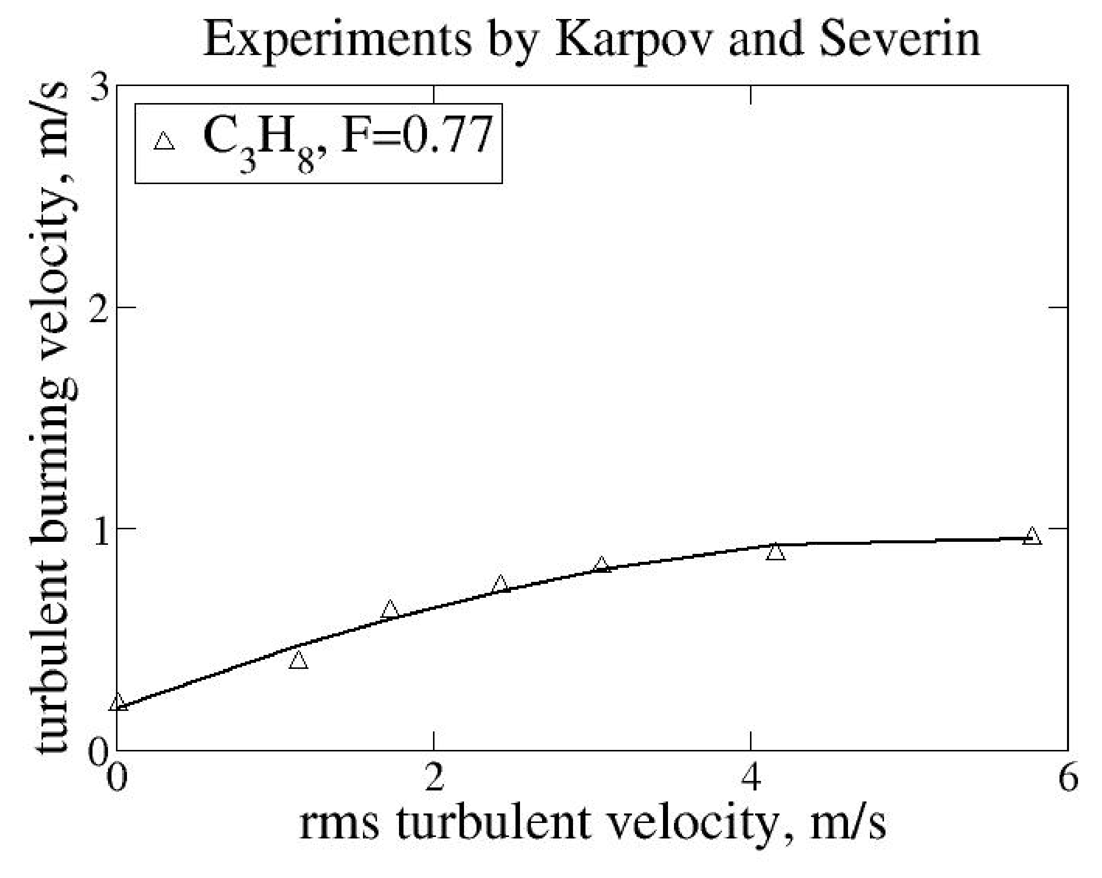
$$\eta \propto \nu^{3/4} \varepsilon^{-1/4};$$

$$u'_\eta \propto \nu^{1/4} \varepsilon^{1/4};$$

$$\mathrm{Re}_\eta = \frac{u'_\eta \eta}{\nu} \approx 1$$

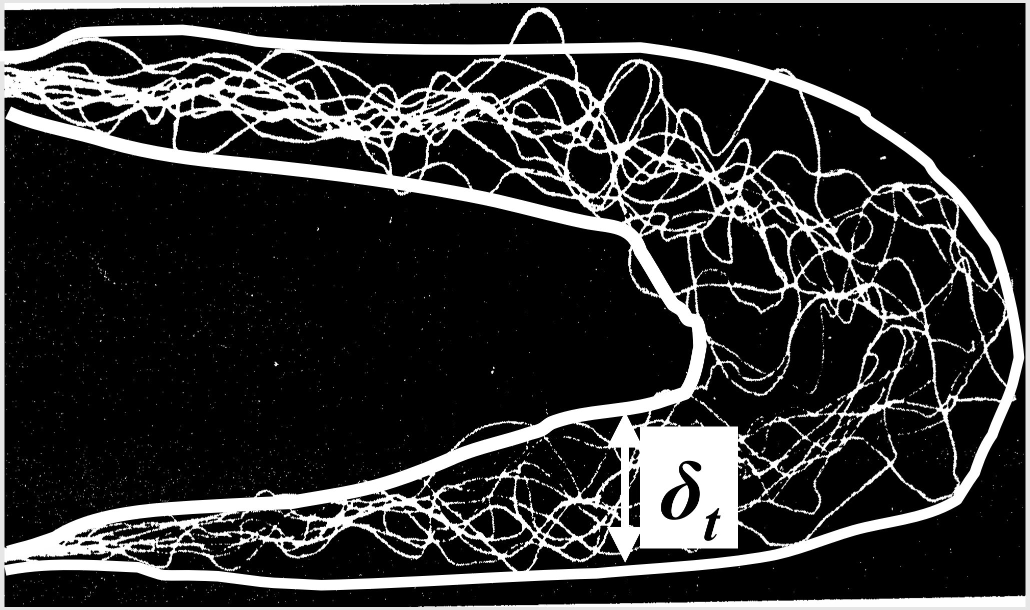
$$k = \frac{2\pi}{\lambda}$$

Effect of Turbulent Velocity on Flame Speed

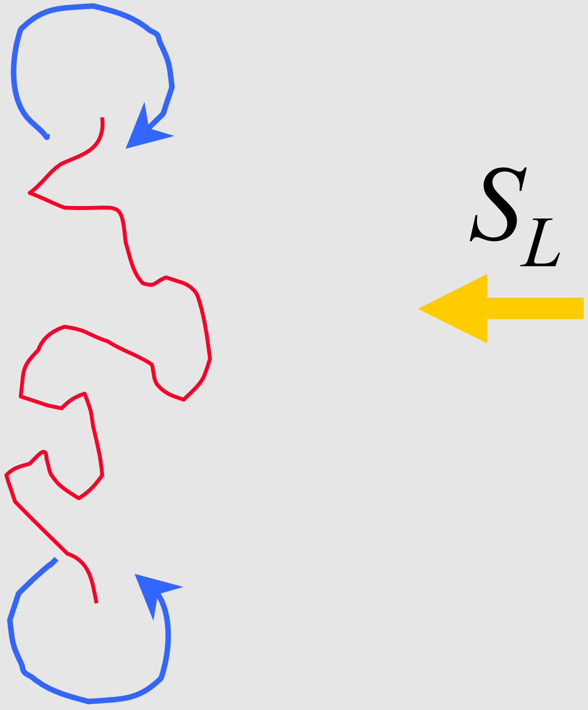


Physical Mechanism of the Increase in Flame Speed by Turbulent Velocity

Picture from the paper by Fox, M.D. and Weinberg, F.J. “An experimental study of burner stabilized turbulent flames in premixed reactants”, Proceedings of the Royal Society of London, A268:222-239, 1962.



$$\delta_L \ll \delta_t$$



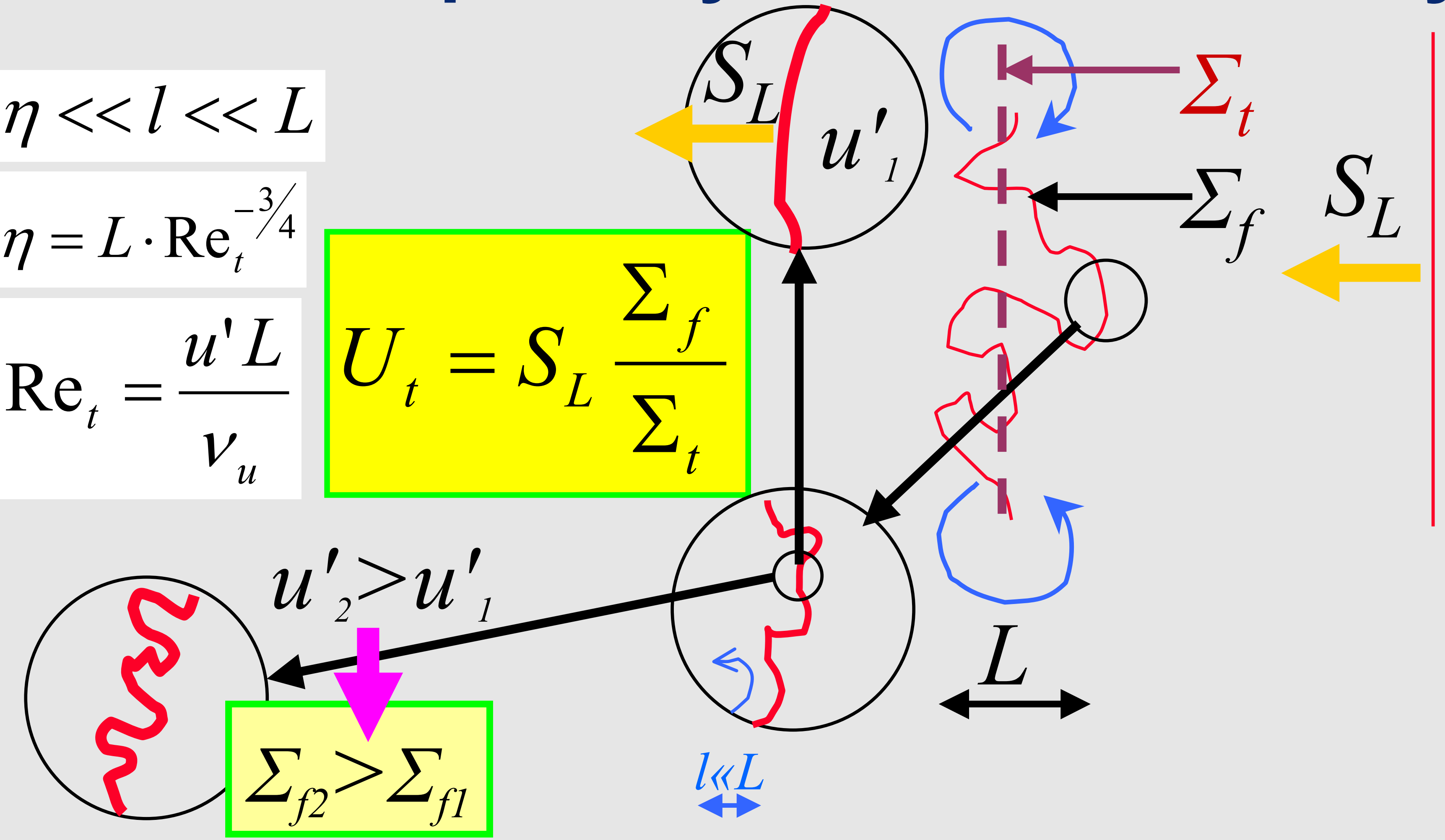
Physical Mechanism of the Increase in Flame Speed by Turbulent Velocity

$$\eta << l << L$$

$$\eta = L \cdot \mathrm{Re}_t^{-3/4}$$

$$\mathrm{Re}_t = \frac{u' L}{\nu_u}$$

$$U_t = S_L \frac{\Sigma_f}{\Sigma_t}$$



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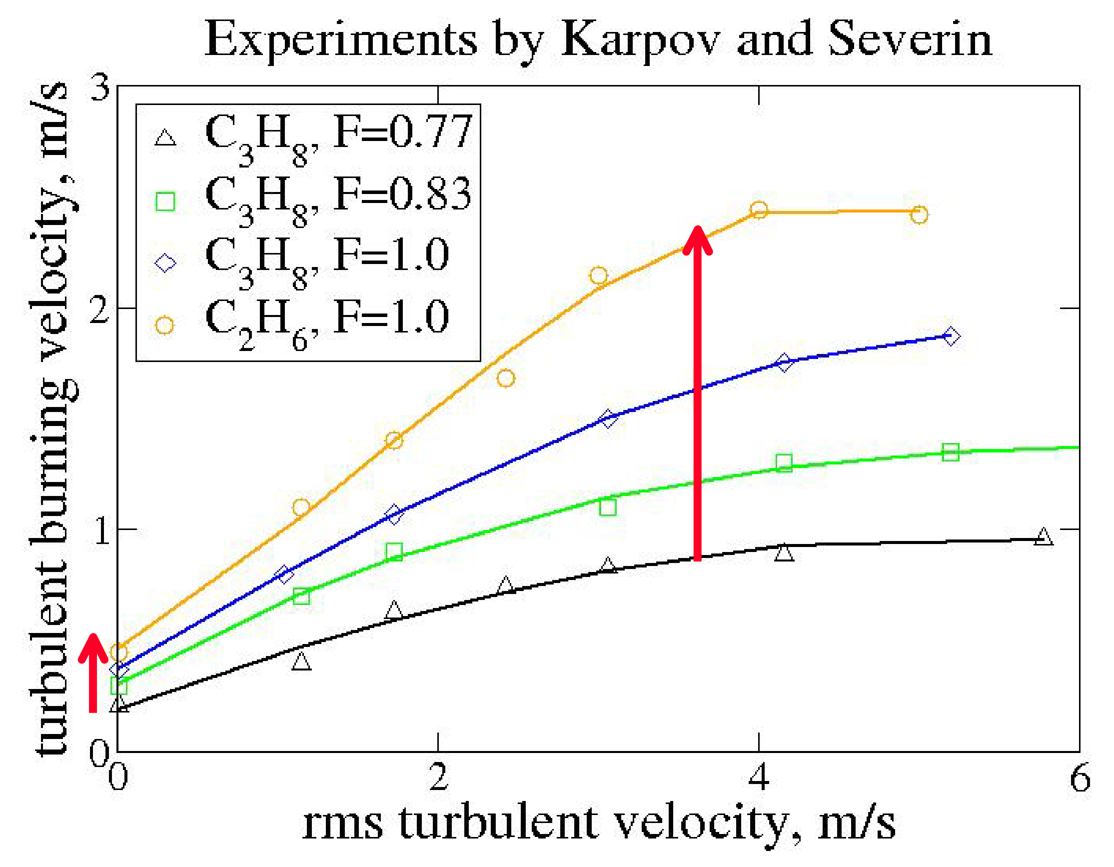
Effect of Laminar Flame Speed on Turbulent Burning Velocity



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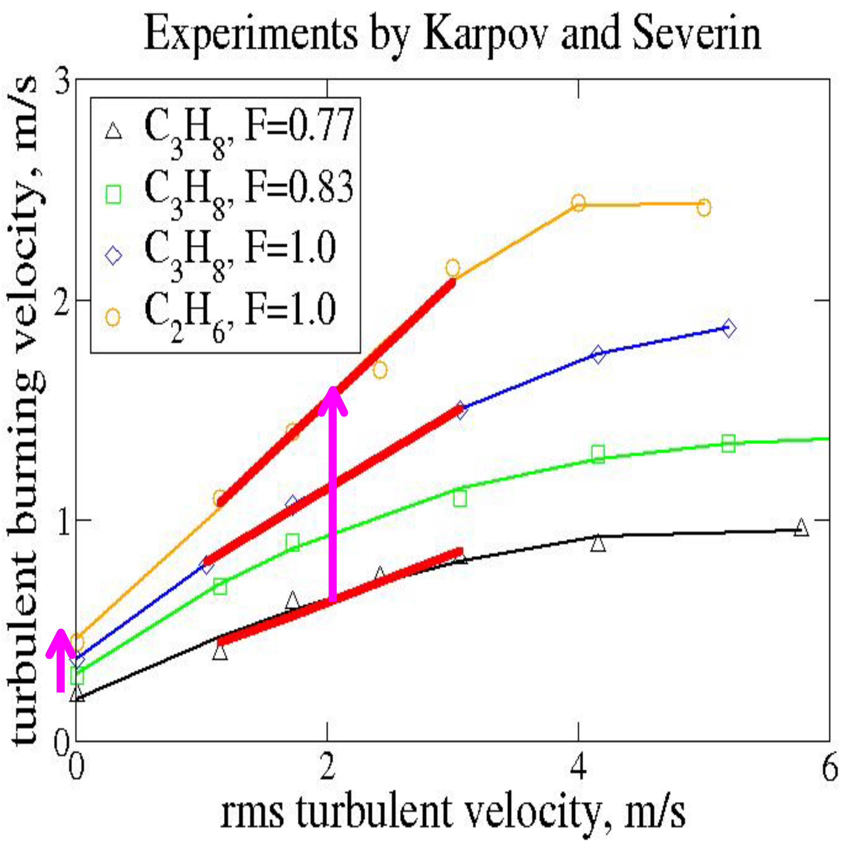
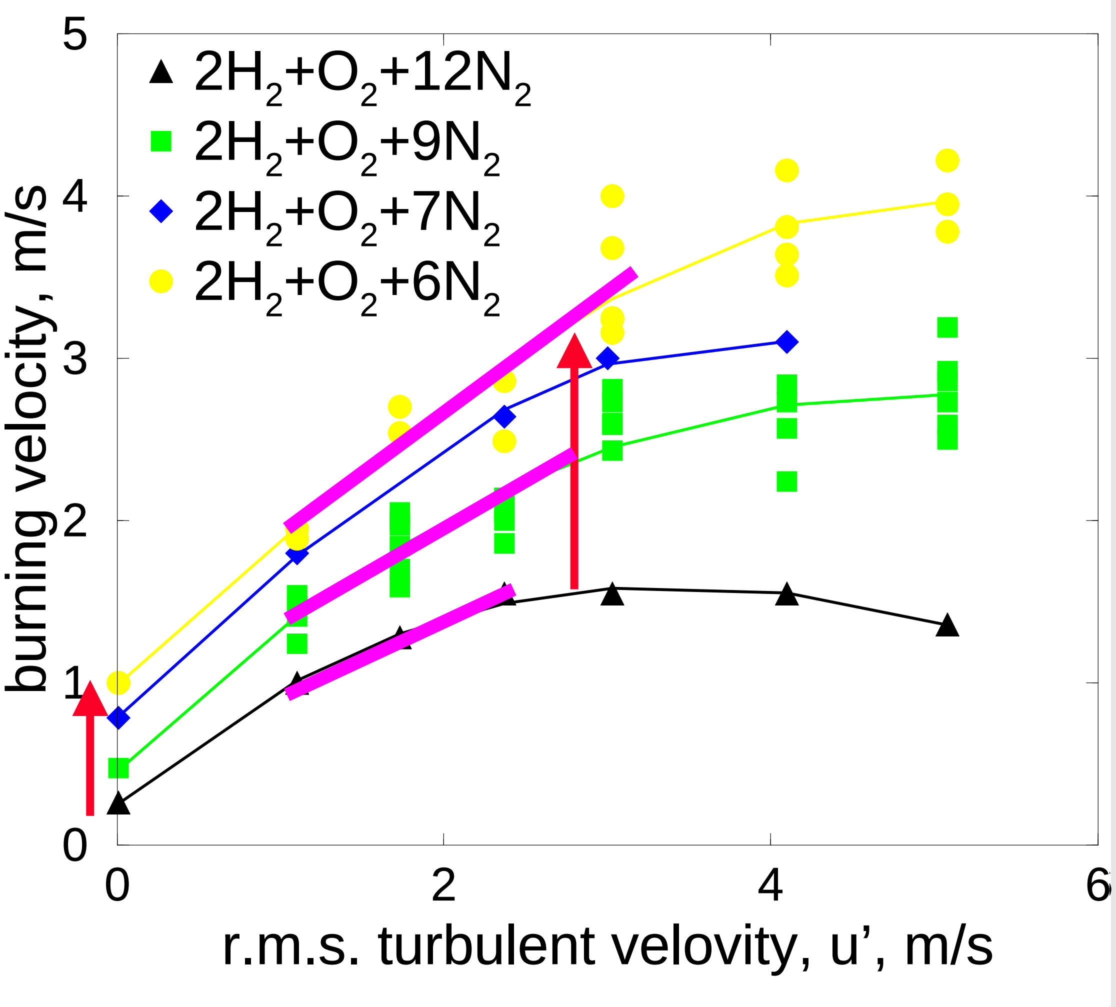


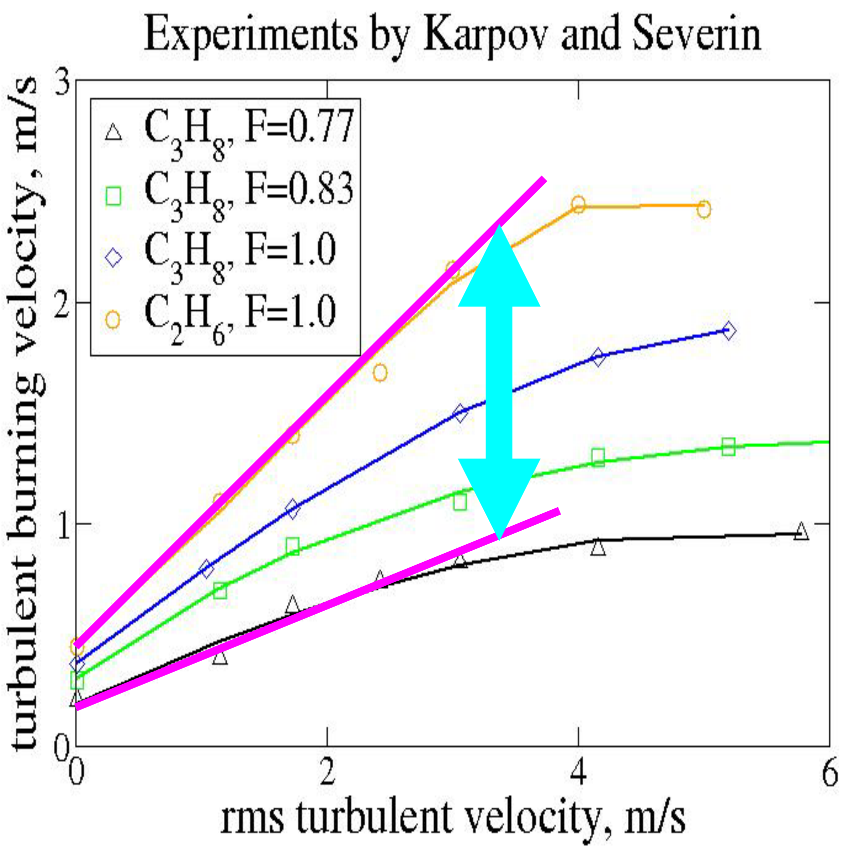
- ➢ ***Turbulent burning velocity U_t is increased by the laminar flame speed S_L, all other things being equal.***

⇨ ***The larger the laminar flame speed, the higher the rate of the increase in the burning velocity by rms turbulent velocity***

Effect of Laminar Flame Speed on Turbulent Burning Velocity



Empirical Parameterization for Turbulent Burning Velocity



$$\boxed{U_t = S_L + u'}$$

\+ ***A linear increase in burning velocity U_t by turbulent velocity u'***

\- $\frac{dU_t}{du'} = \text{const}$

Empirical Parameterization for Turbulent Burning Velocity

$$\frac{U_t}{u'} = F_1\left(\frac{u'}{S_L};\frac{\delta_L}{L}\right) = F\left(\frac{u'}{S_L};\mathrm{Re}_t;\mathrm{Pr}\right) = F_3(\mathrm{Da};\mathrm{Ka};\mathrm{Pr})$$

$$\mathrm{Re}_t\ \mathrm{Pr} = \frac{u'}{S_L}\cdot\frac{L}{\delta_L}; \quad \mathrm{Da} = \frac{S_L}{u'}\cdot\frac{L}{\delta_L}; \quad \mathrm{Ka} \propto \left(\frac{u'}{S_L}\right)^2 \mathrm{Re}_t^{-1/2}$$

$$\boxed{U_t = \mathrm{const}\cdot u'^a \cdot L^b \cdot S_L^c \cdot \nu_u^d}$$

$$a+c+d=1; \qquad a+b+c+2d=1$$

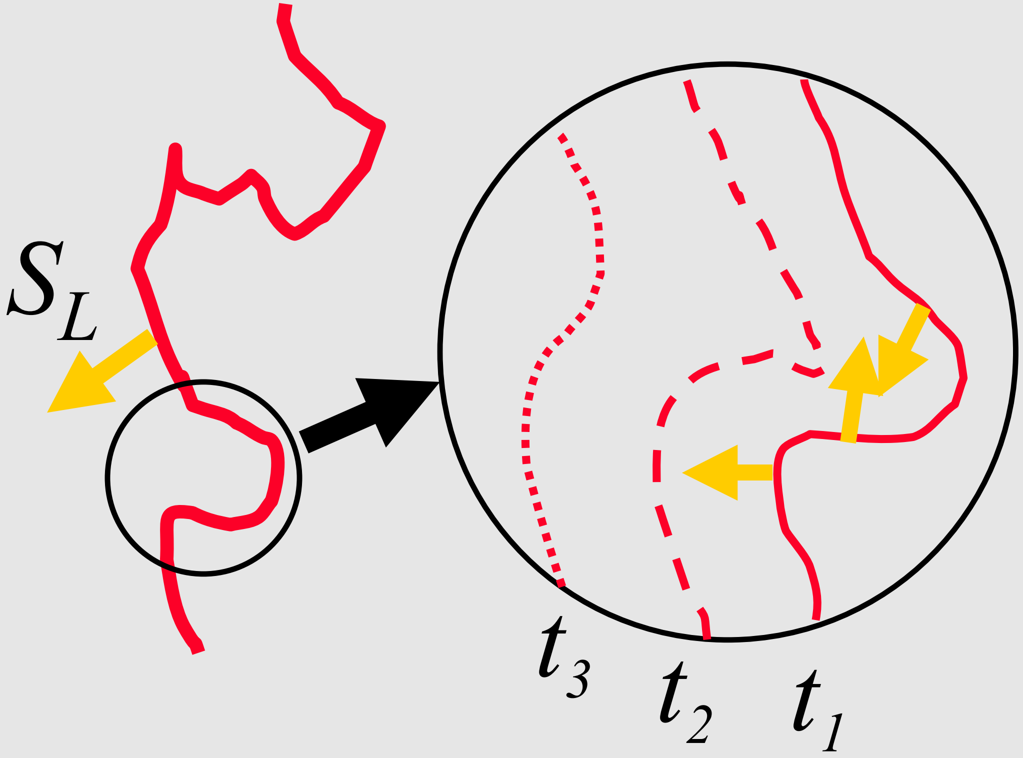
Empirical Parameterization for Turbulent Burning Velocity

$$U_t = \mathrm{const} \cdot u'^{a} \cdot L^{b} \cdot S_L^{c} \cdot \nu_u^{d}$$

$$\underbrace{a \approx 0.5\text{-}0.75 \qquad\qquad c = 0.5\text{-}0.6}_{\Downarrow}$$

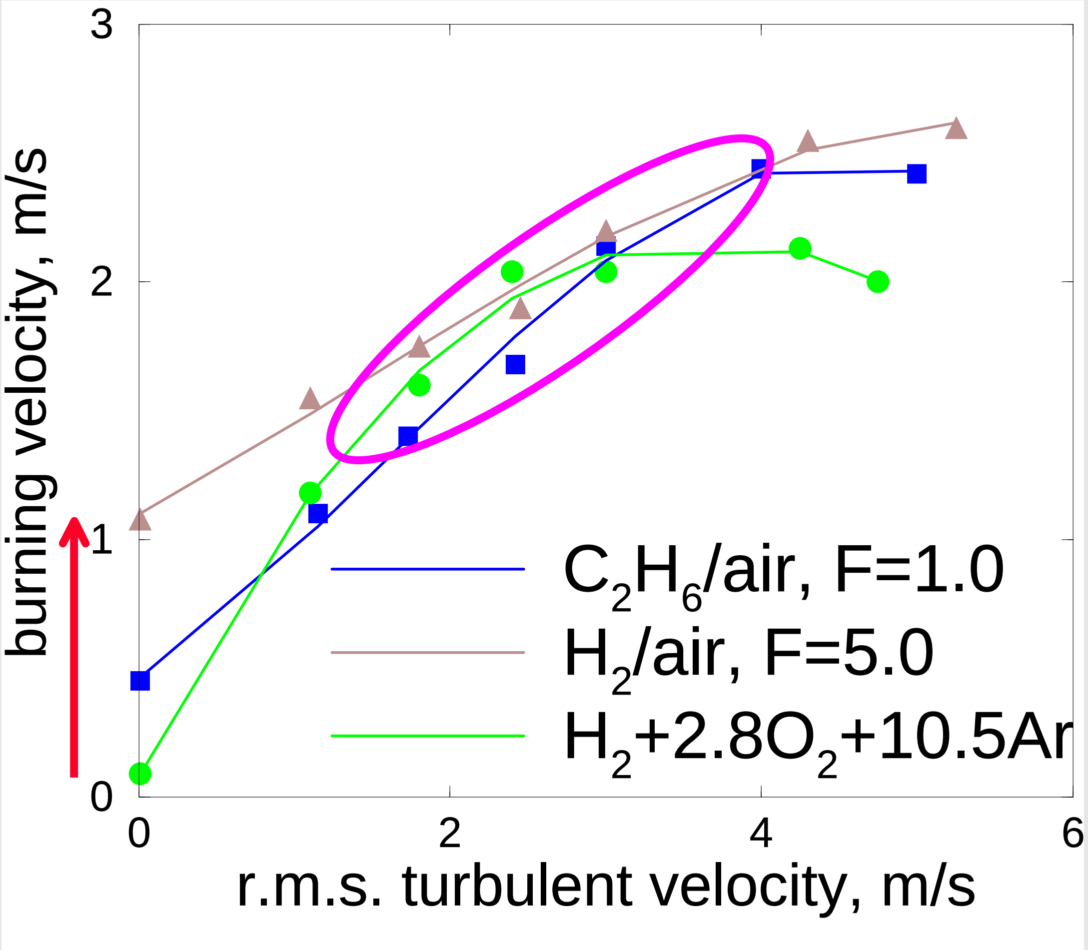
$$\boxed{\frac{dU_t}{du'} \textbf{ is increased by } S_{\mathrm{L}}\textbf{!}}$$

Why Does Turbulent Burning Velocity Depend Non-Linearly on the Laminar Flame Speed?

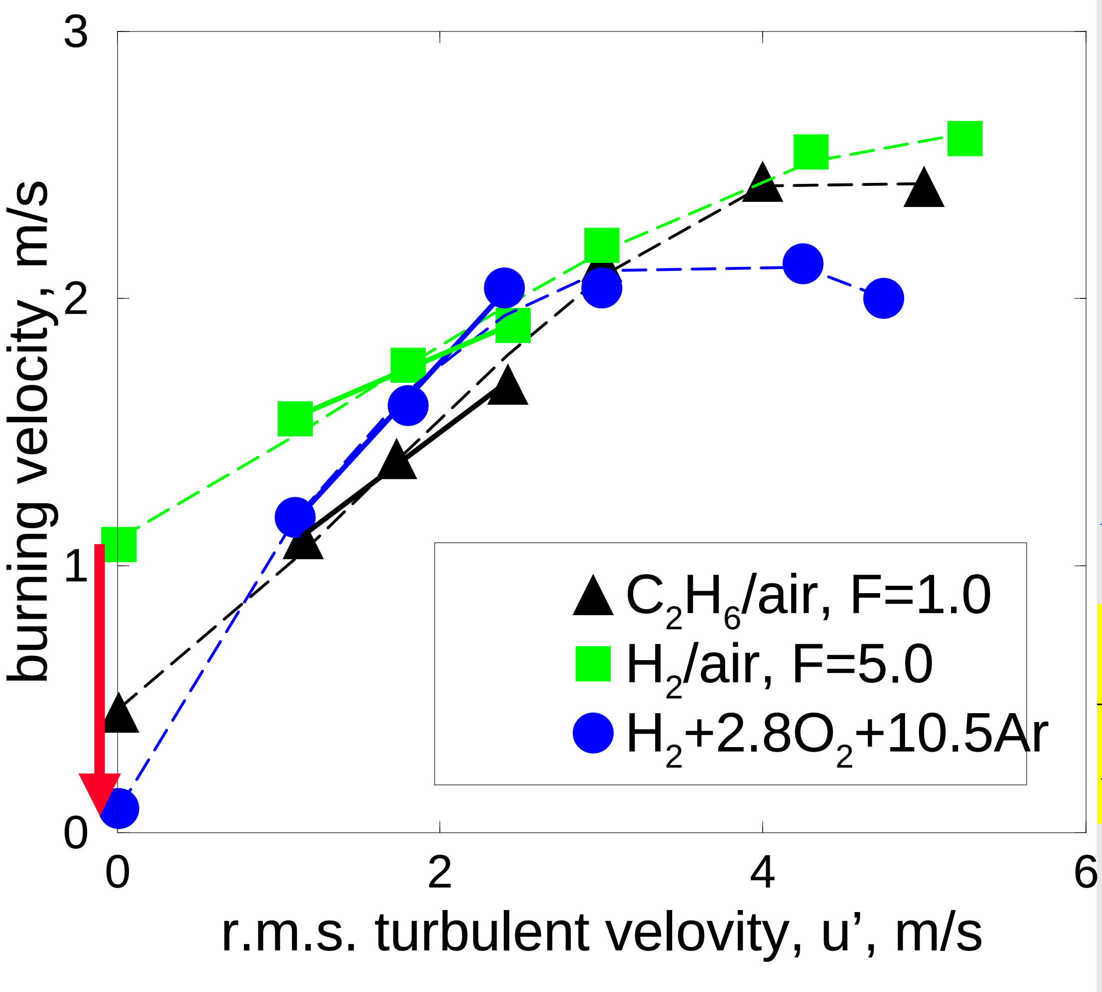


Self-propagation of laminar flame fronts reduces the instantaneous flame surface area, i.e., Σ_f decreases when S_L increases!

Is Turbulent Burning Velocity Always Increased by the Laminar Flame Speed?



Strong Effect of the Lewis Number on Increase in Burning Velocity



Ordinary mixtures:

$$\frac{dU_t}{du'} \propto \sqrt{S_L}$$

Lean to rich hydrogen flames:

$$\frac{1}{\sqrt{S_L}} \cdot \frac{dU_t}{du'} \Bigg/ \frac{1}{\sqrt{S_L}} \cdot \frac{dU_t}{du'} \approx 7$$

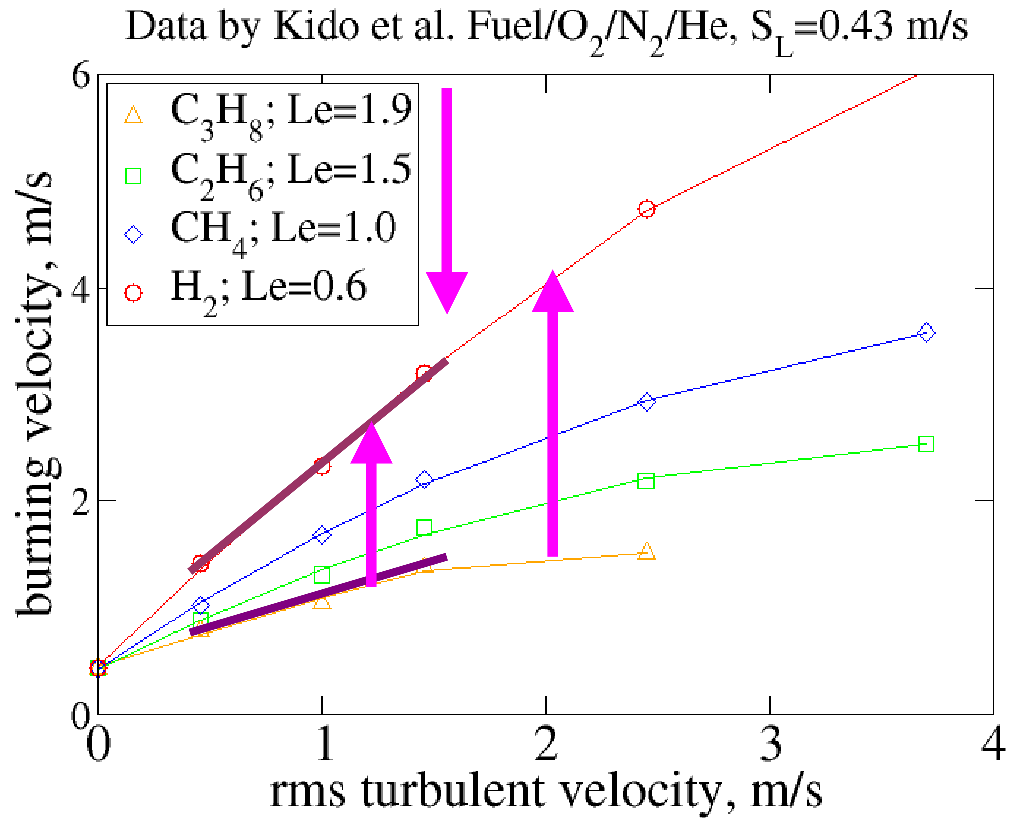
Seven times!!!

An Important Peculiarity of Hydrogen-Air Mixtures

- Molecular diffusion coefficient of hydrogen D_{H2} in the air on the order on 0.6 cm^2/s
- Molecular diffusion coefficient of oxygen D_{O2} in the air on the order on 0.2 cm^2/s
- Molecular heat diffusivity of the air κ on the order on 0.2 cm^2/s

Hydrogen-based Lewis number $\boxed{Le_{H2}=\kappa/D_{H2}}$ is substantially lower than unity in lean mixtures!

Effect of the Lewis Number on Turbulent Burning Velocity



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Temperature Variations in Curved Flamelets

$$\boxed{J_A \cdot \Sigma_A \cdot \delta t = \delta H \cdot \Sigma_A \cdot \delta z + J_B \cdot \Sigma_B \cdot \delta t}$$

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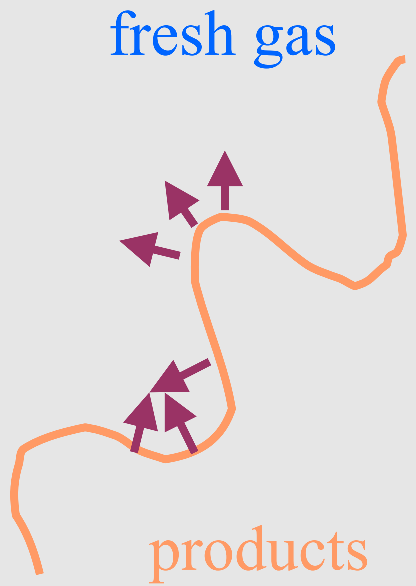
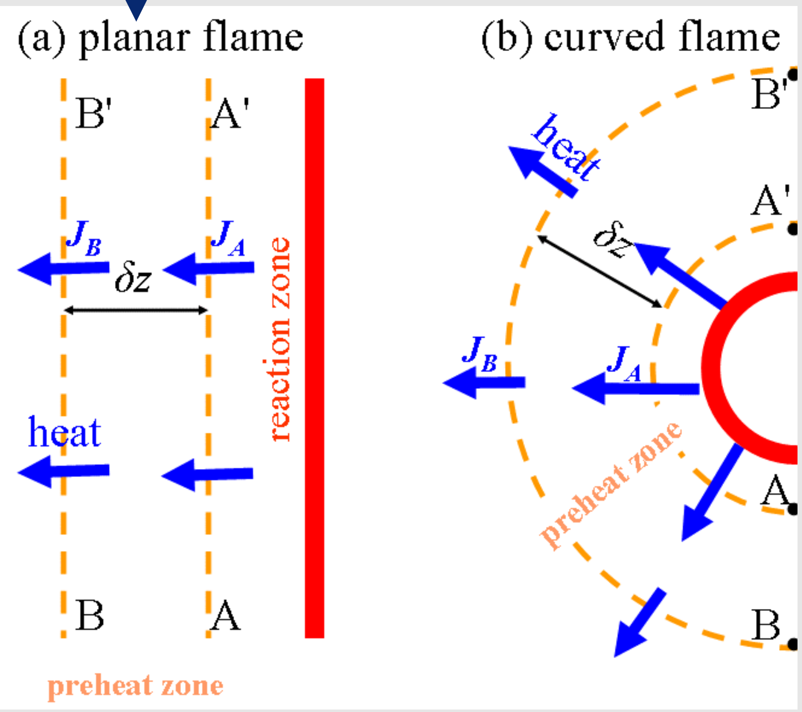


heat conductivity



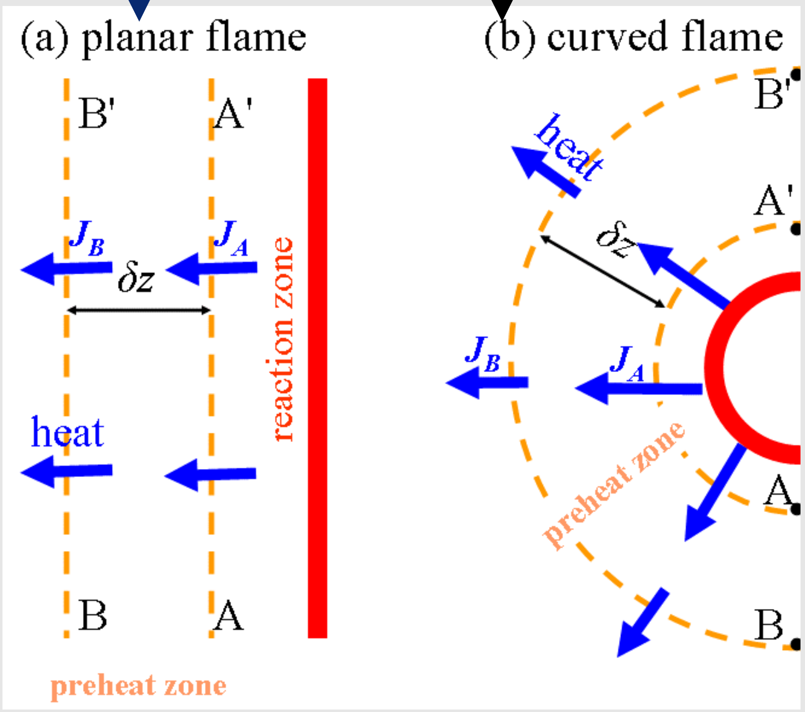
Temperature Variations in Curved Flamelets

$$J_A \cdot \sigma \cdot \delta t = \delta H \cdot \delta z + J_B \cdot \delta t$$

$$J_A \cdot \delta t = \delta H \cdot \delta z + J_B \cdot \delta t$$

$$\sigma = \Sigma_A / \Sigma_B < 1$$

heat conductivity



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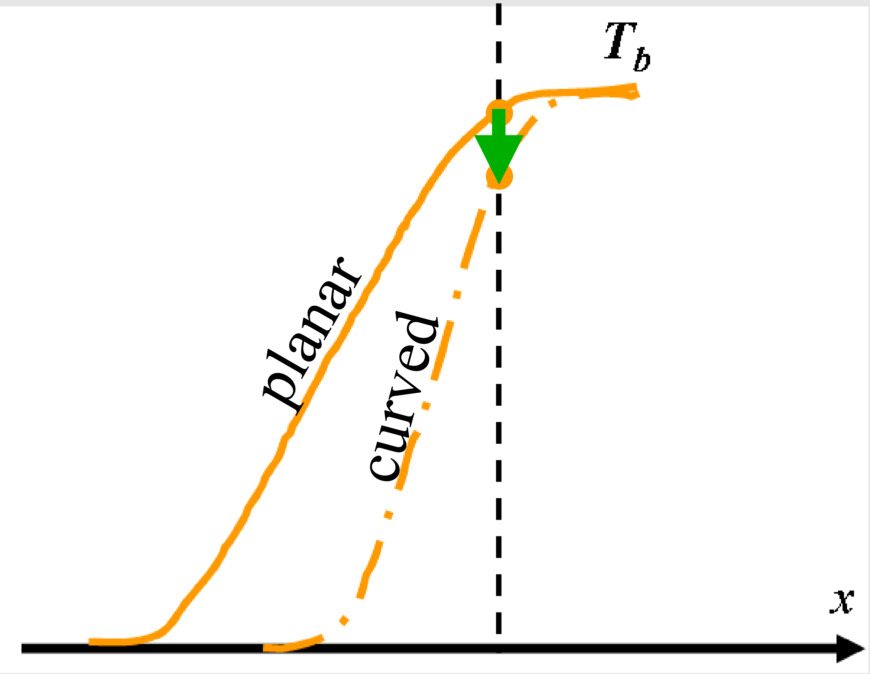
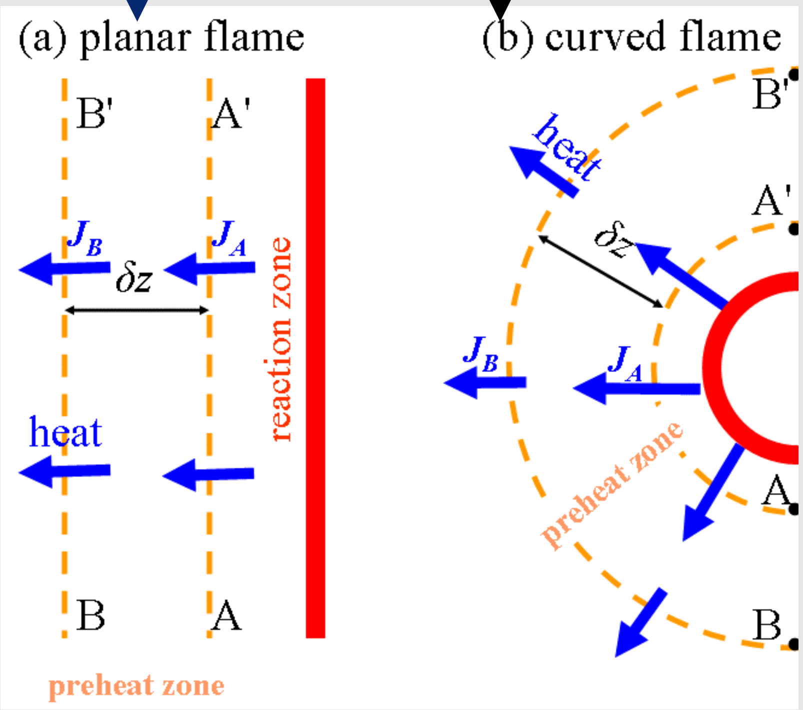
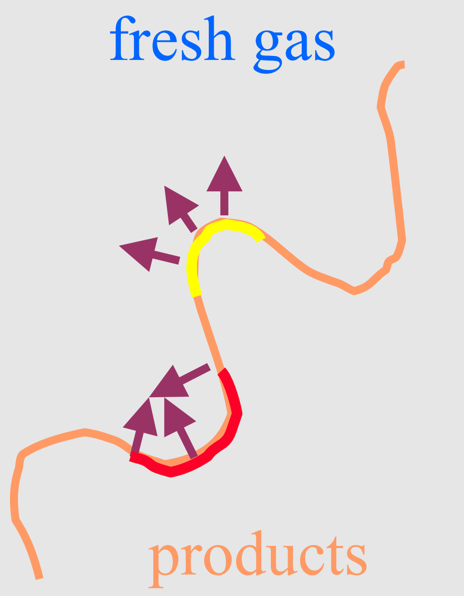




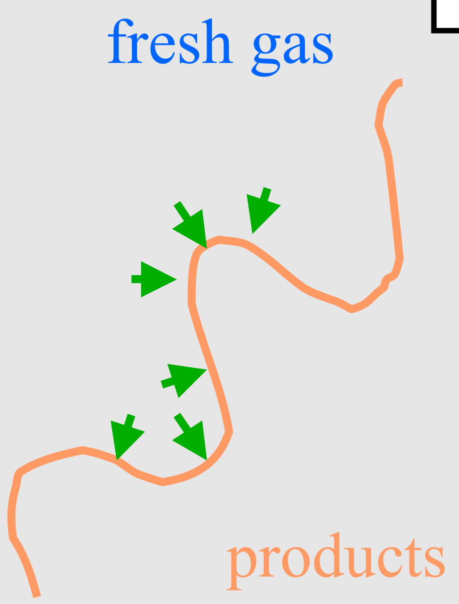
Mass Fraction Variations in Curved Flamelets

$$J_B \cdot \sigma \cdot \delta t = \delta Y \cdot \delta z + J_A \cdot \delta t$$

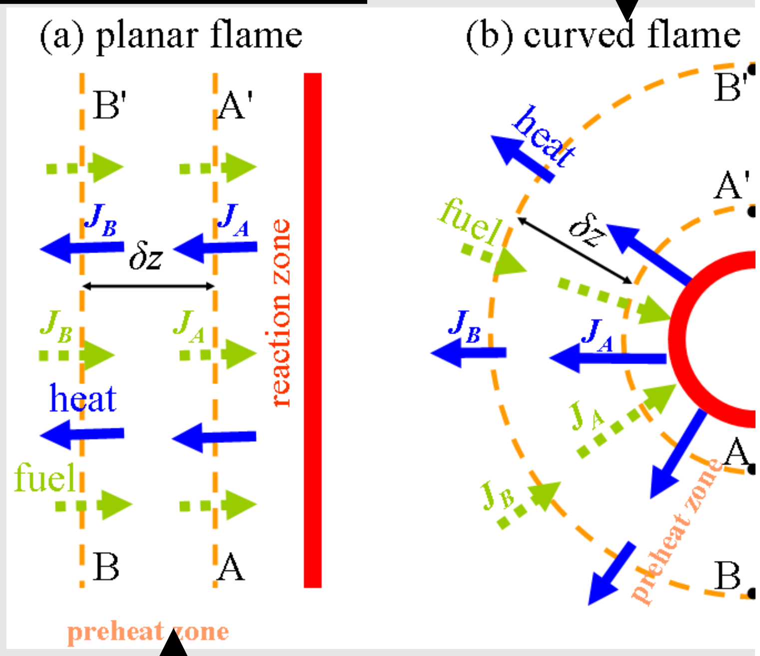
$$\sigma = \Sigma_B / \Sigma_A > 1$$



heat conductivity

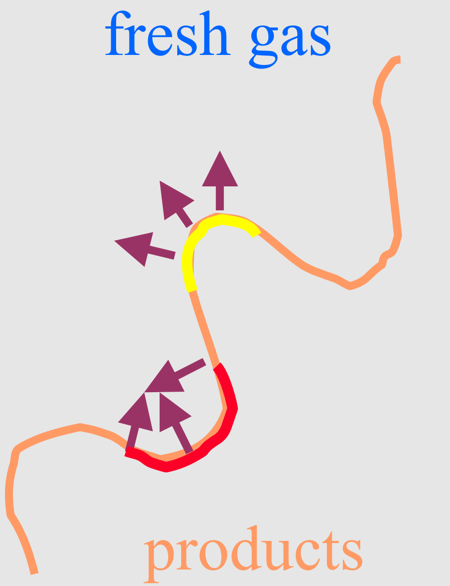


diffusivity

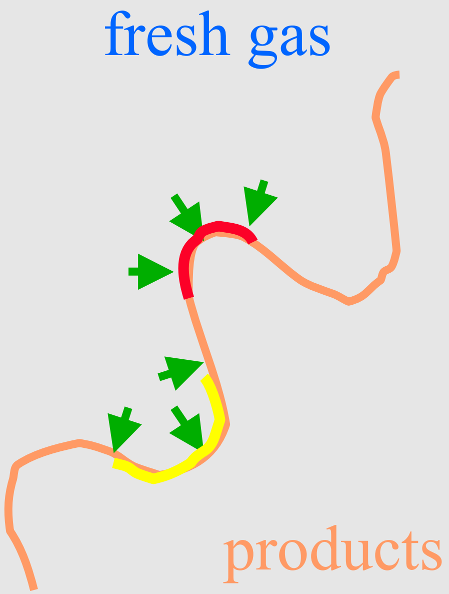


$$J_A \cdot \delta t = \delta Y \cdot \delta z + J_B \cdot \delta t$$

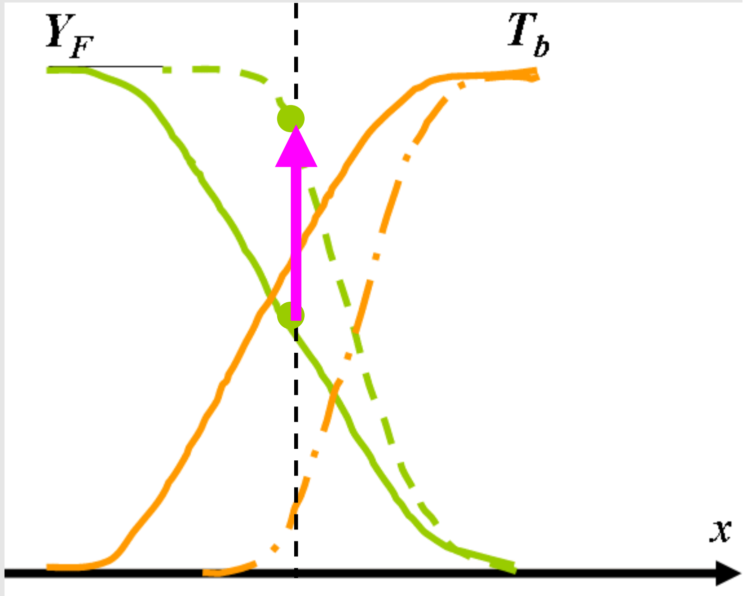
Mass Fraction Variations in Curved Flamelets



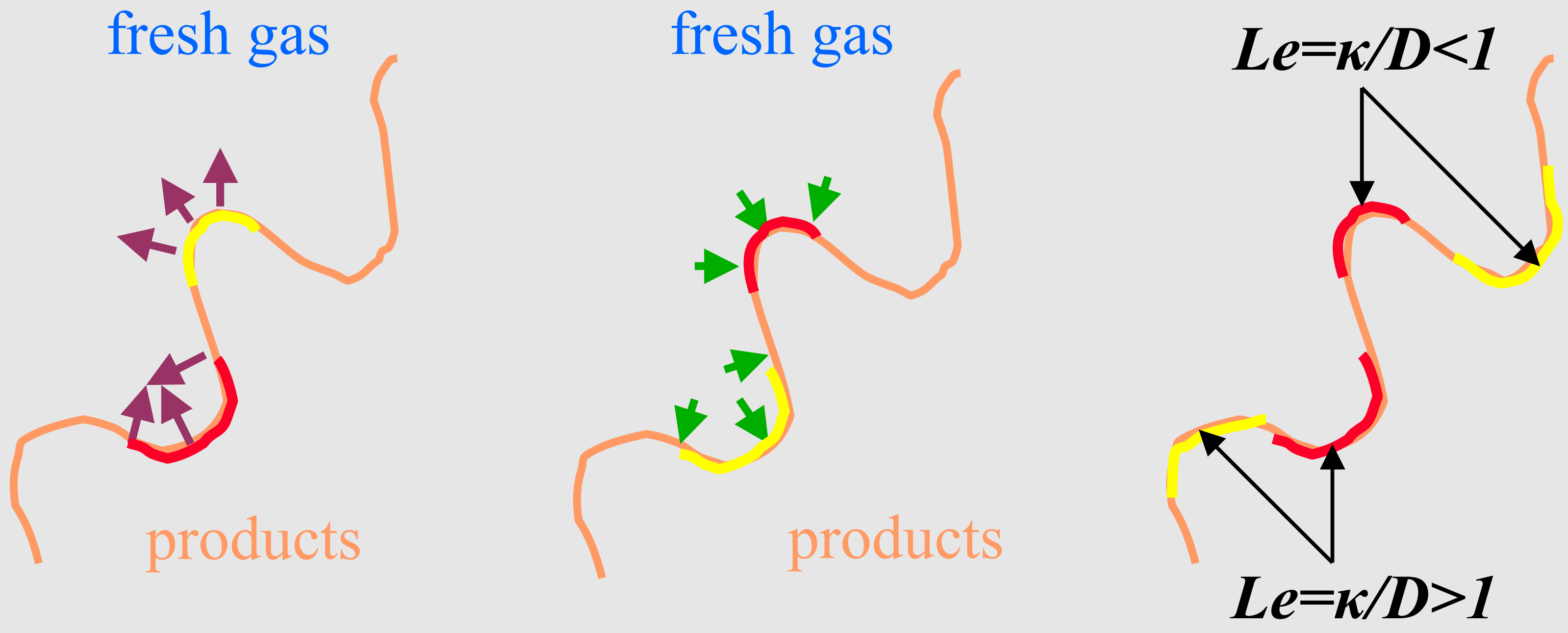
heat conductivity



diffusivity



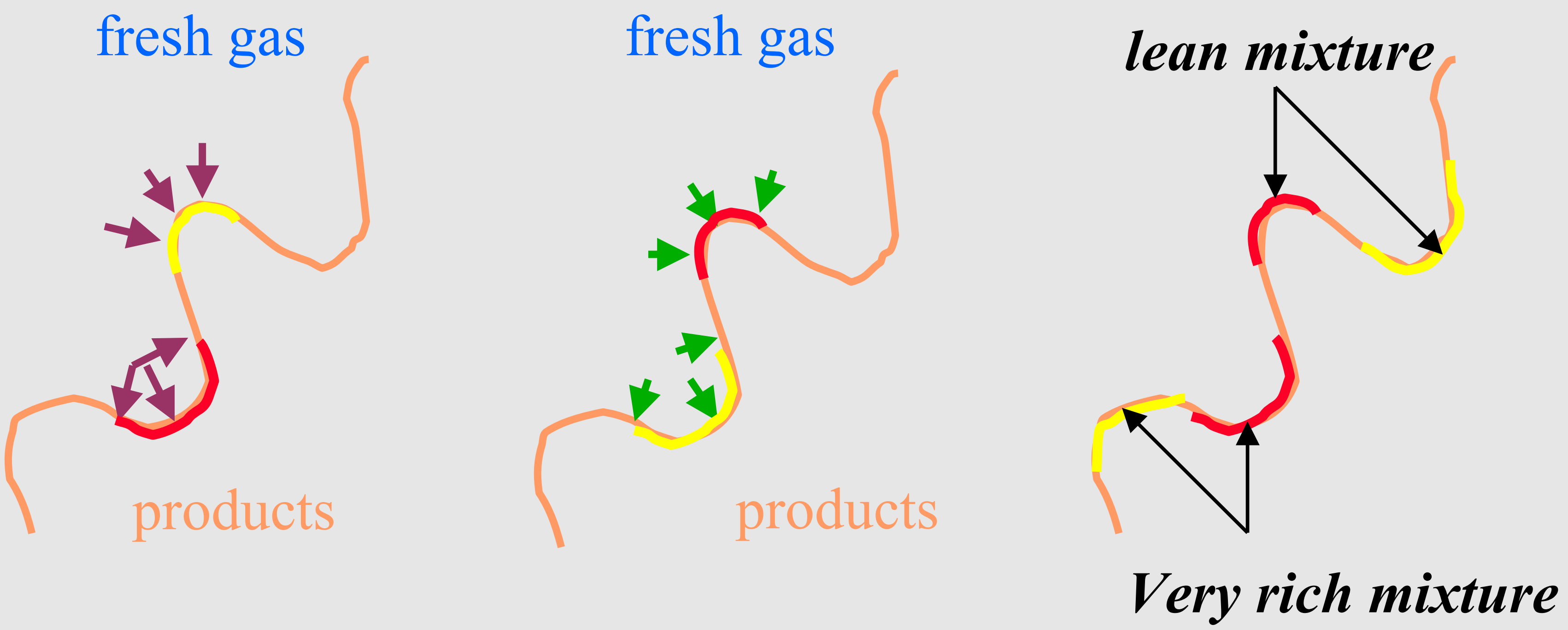
Effect of the Lewis Number on Burning Rate in Curved Flamelets



heat conductivity

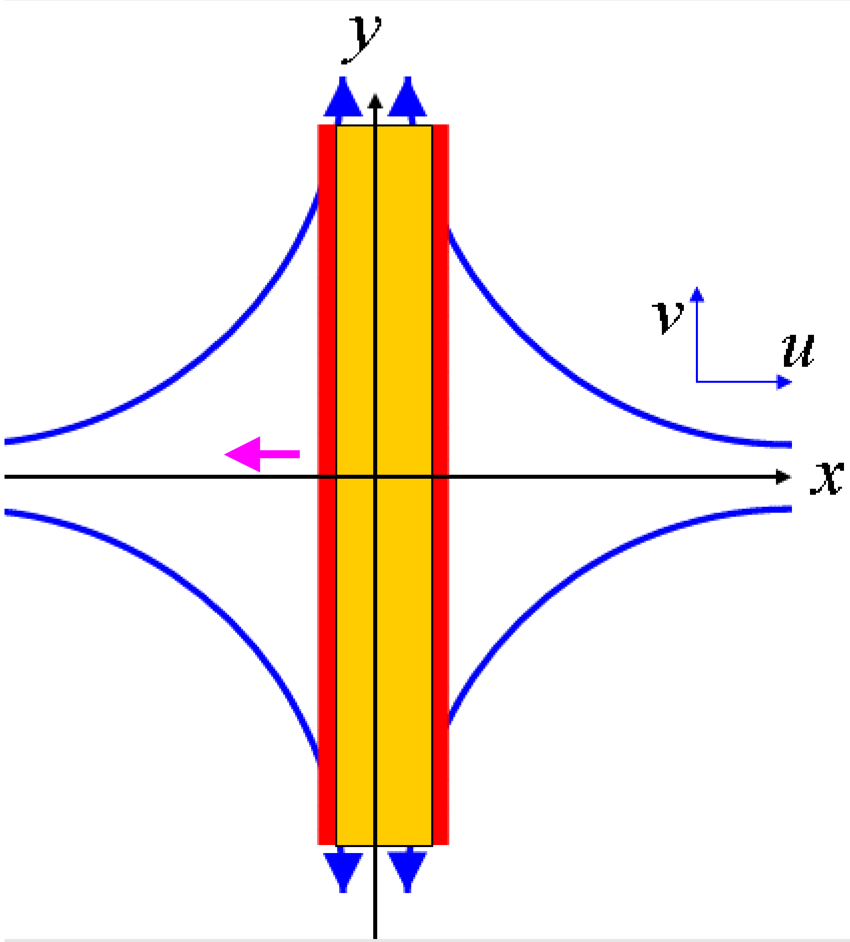
diffusivity

Effect of Molecular Diffusivity on Burning Rate in Curved Flamelets



diffusion of oxygen **diffusion of hydrogen**

Temperature Variations in Strained Flamelets



Reaction zone:

$$\boxed{a\left.\frac{dT}{dx}\right|_r = -\int_{\delta_r} w\,dx}$$

$$\underbrace{u\frac{dT}{dx} = a\overbrace{\frac{d^2T}{dx^2}}}+w$$

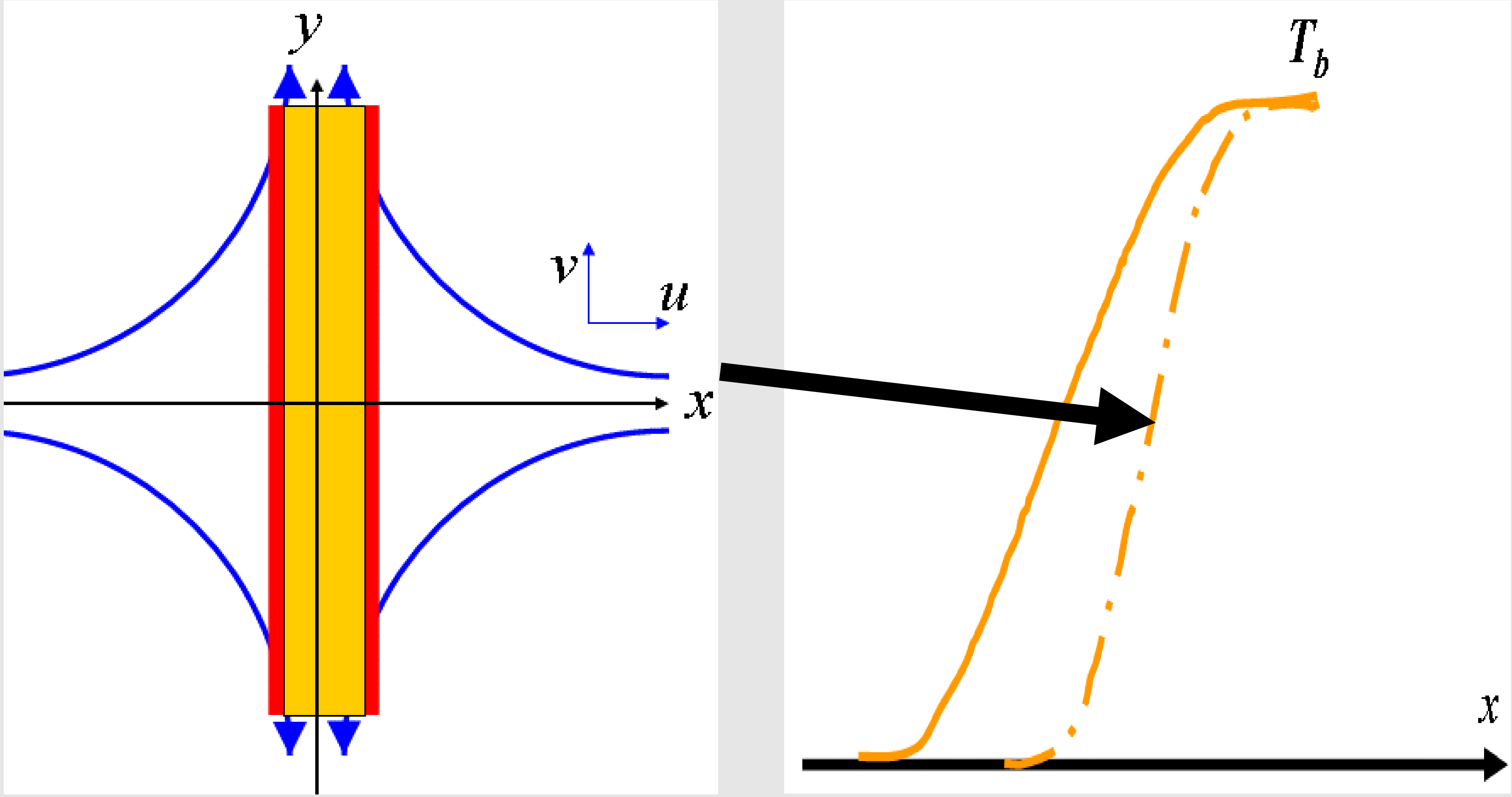
Preheat zone:

$$\boxed{u\frac{dT}{dx} = a\frac{d^2T}{dx^2}}$$

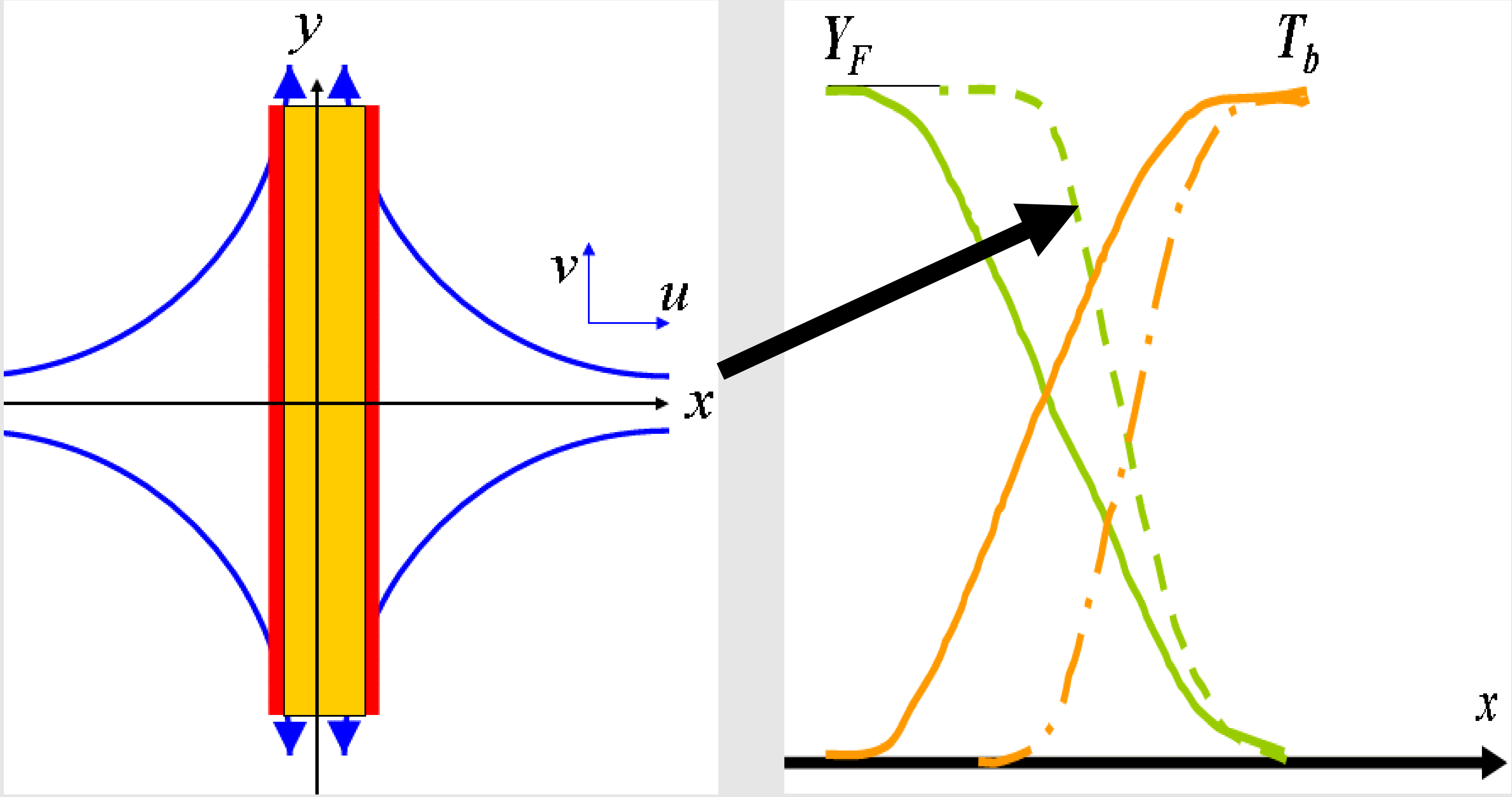
$$u_r = S_L \longleftarrow u_r T_r = a\left.\frac{dT}{dx}\right|_r$$

ρ=const: $u=-\sigma x$; $v=\sigma y$

Temperature Variation in Strained Flamelets

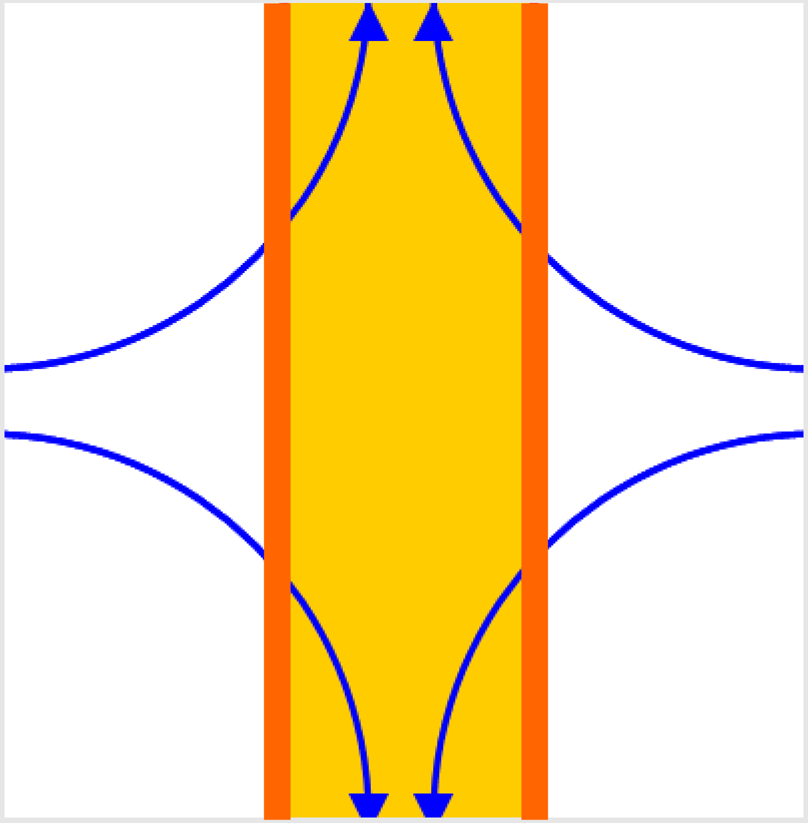


Mass Fraction Variation in Strained Flamelets

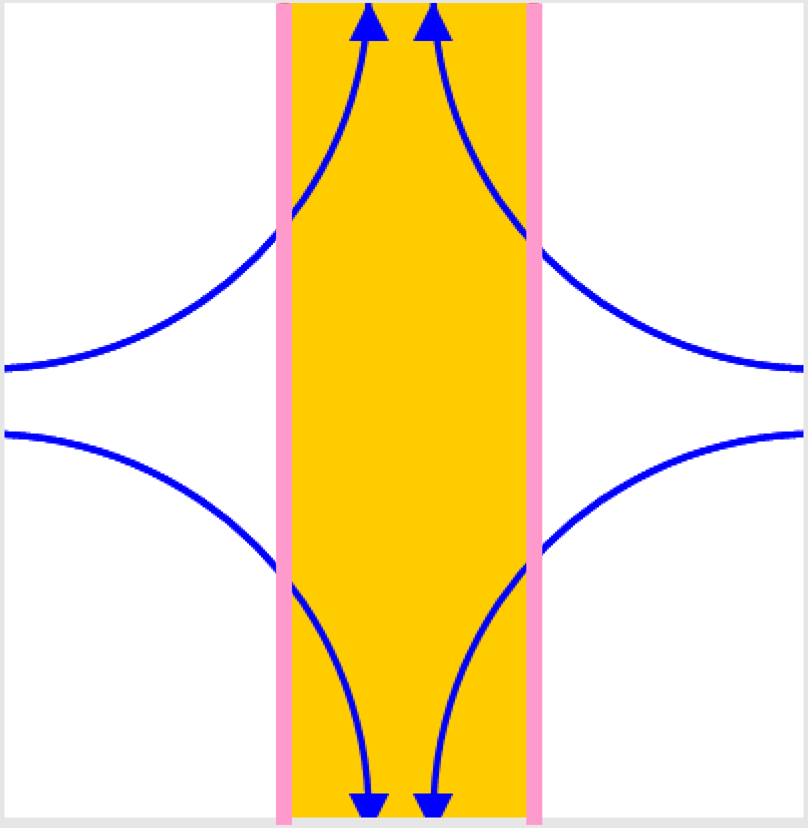


Effect of the Lewis Number on Burning Rate in Strained Flamelets

$a<D$ (Le<1)



$a>D$ (Le>1)



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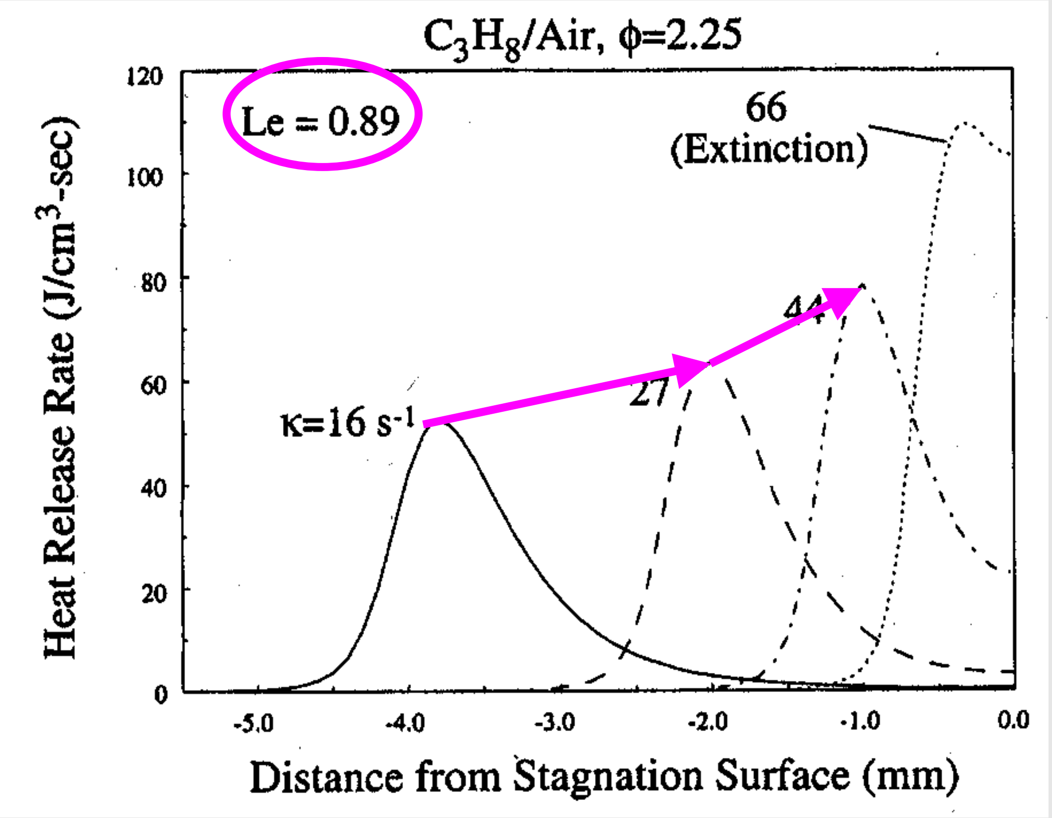

From the paper by Law, C.K. and Sung, C.J.,
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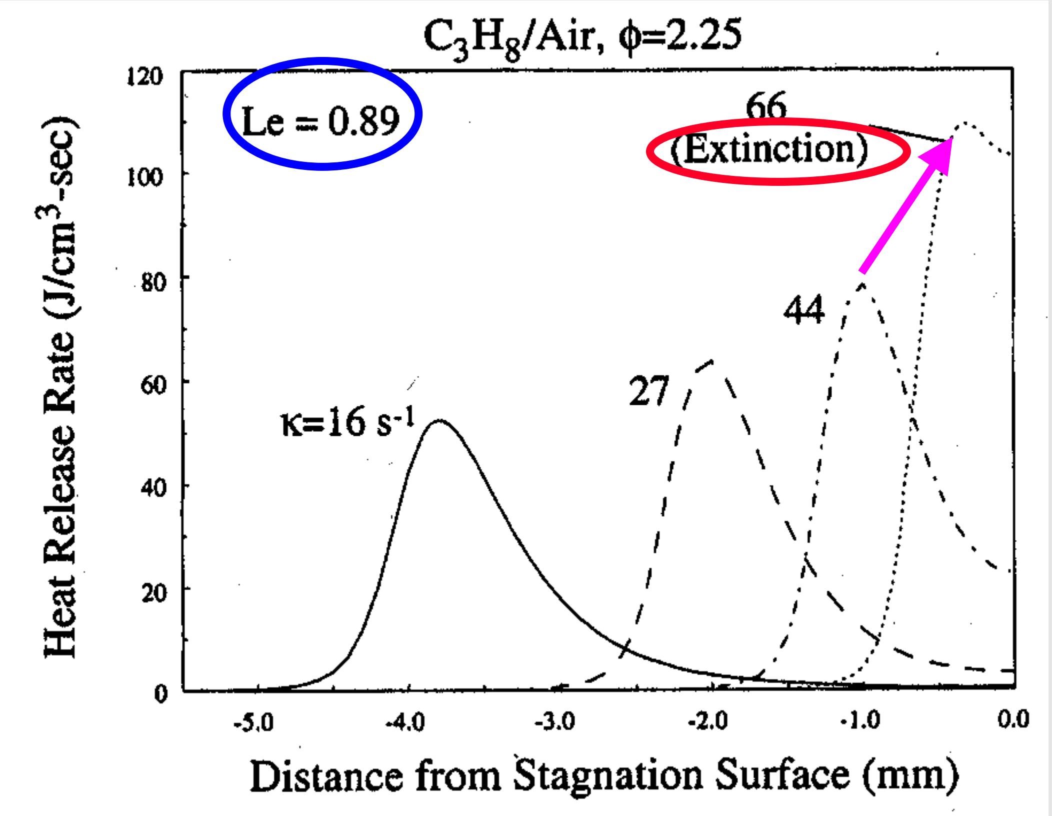
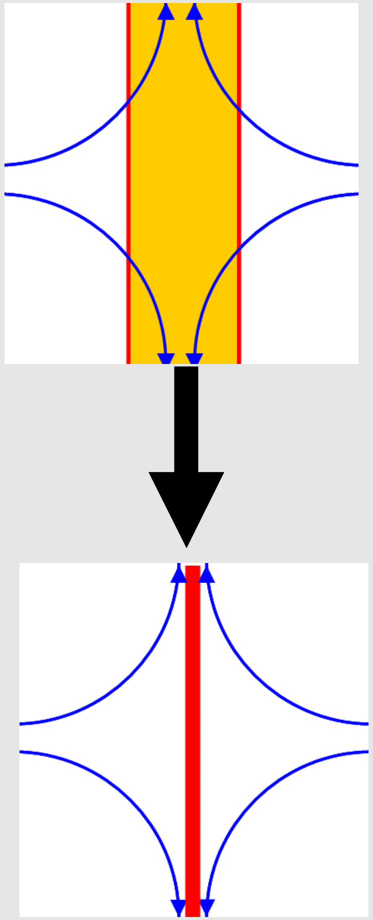
Progress in Energy and Combustion Science 26: 459-505 (2000).

Effect of the Lewis Number on Quenching of Strained Flamelets





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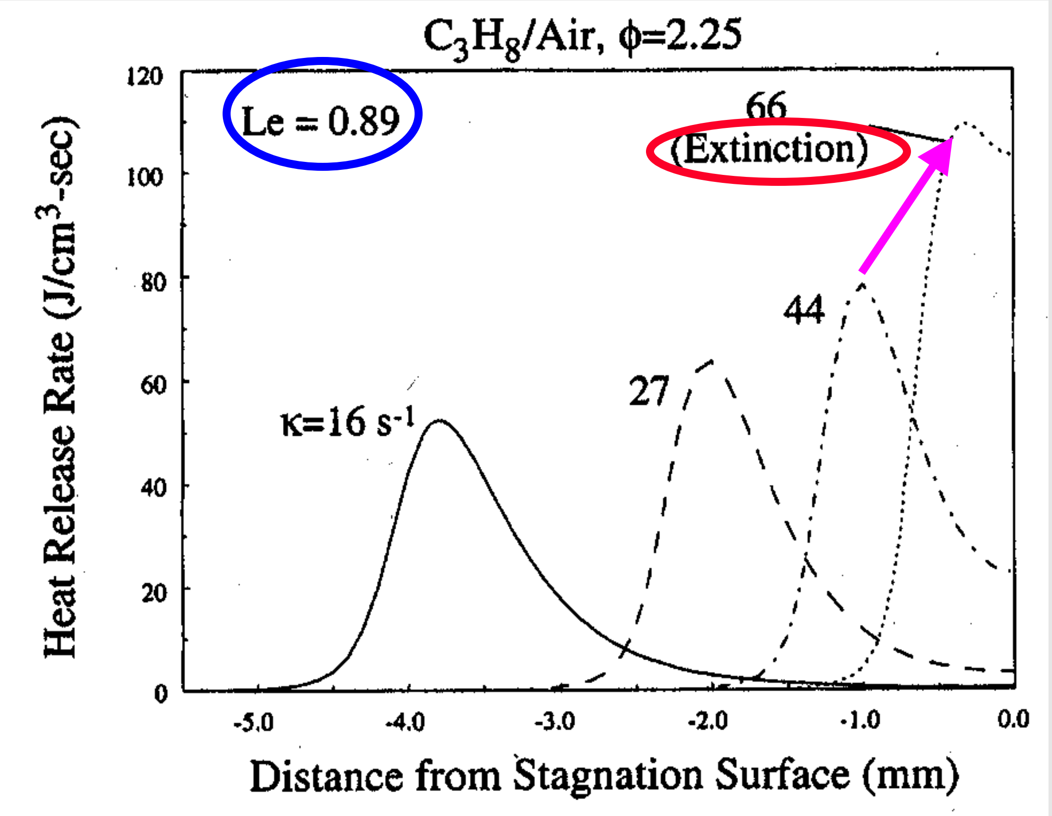
Effect of the Lewis Number on Quenching of Strained Flamelets



From the paper by Law, C.K. and Sung, C.J.,
"Structure, aerodynamics, and geometry of premixed flames",
Progress in Energy and Combustion Science 26: 459-505 (2000).

- Radiation heat losses
- Finite thickness of the reaction zone
- Complex chemistry

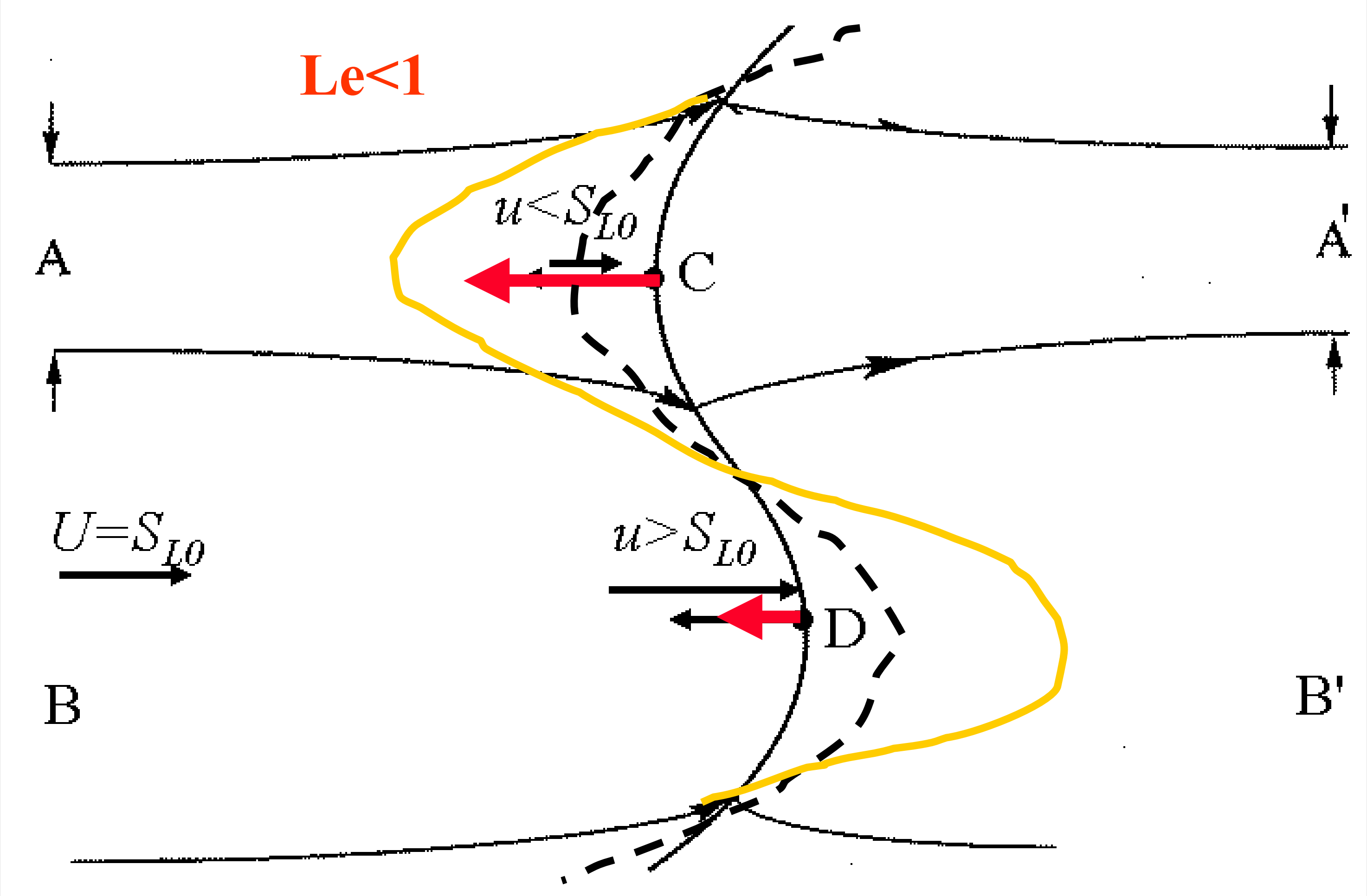
Quenching strain rate depends substantially on the Lewis number: quenching is impeded when Le decreases!

Why does Molecular Transport Substantially Affect Premixed Turbulent Combustion at High Reynolds Number?

$$\boxed{U_t = \boxed{S_L}\,\frac{\Sigma_f}{\Sigma_\perp}} \longrightarrow \boxed{U_t = \boxed{\bar{u}_c}\,\frac{\Sigma_f}{\Sigma_\perp}}$$

$$\boxed{\bar{u}_c = \frac{1}{\rho_u Y_u \Sigma_f}\underbrace{\left\langle \iiint \overline{\rho}\widetilde{w}\cdot dl\cdot d\Sigma \right\rangle_{\text{flamelet}}}_{\text{Local variations in consumption velocity}} \cdot \underbrace{P\left(\dot{s} \le \dot{s}_q\right)}_{\text{Local quenching}}}$$

Flame Instabilities



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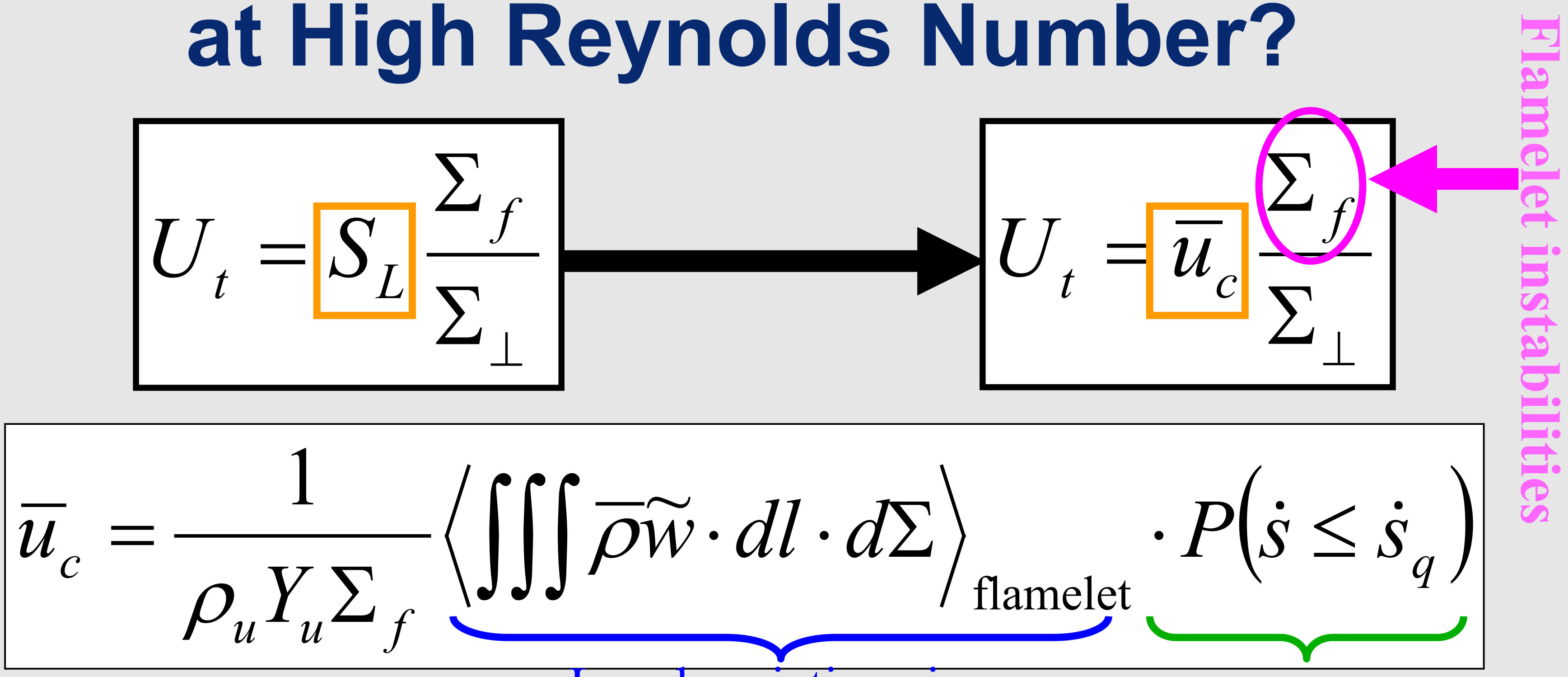

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Flamelet instabilities

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Modeling of turbulent combustion of lean hydrogen-air mixtures?