Lecture 6:

Ch 6: Laminar Premixed Flame

Recap

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- Limit phenomena:
  - Ignition - Autoignition in detail & spark ignition briefly, MIE
  - Introduced conserved scalar concept
  - Extinction - WSR – idealisation of combustion in many practical devices
  - These phenomena result because of competing effects between heat loss/transport and heat generation (combustion)

$$\frac{\partial \rho Y_i}{\partial t} = w_i$$

$$\frac{\partial \rho Y_i}{\partial t} + \frac{\partial \rho U Y_i}{\partial x} = \frac{\partial}{\partial x}\left(\rho D \frac{\partial Y_i}{\partial x}\right) + w_i$$

Objective – Premixed Flames

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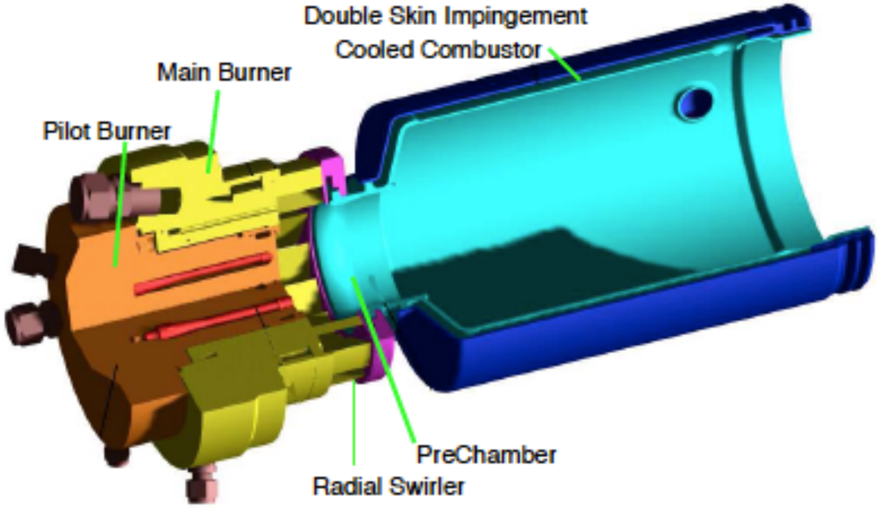
- Develop a simple theory for flame propagation

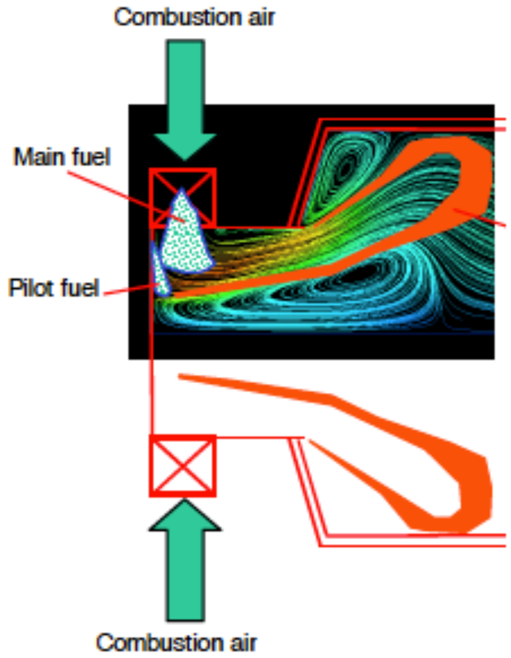
- Develop understanding of flame speed or burning velocity, its dependence on T, p, ϕ

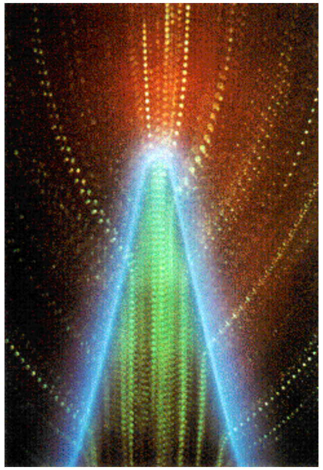
- Discuss flammability limits

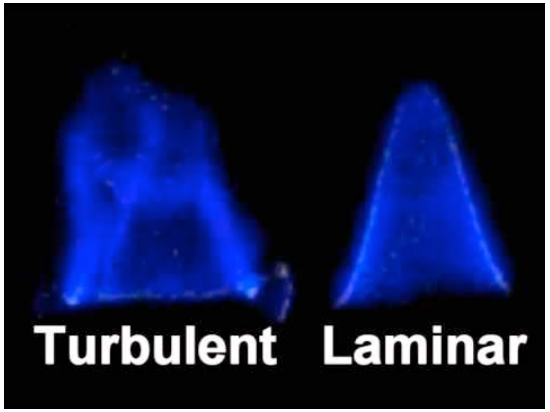
Why study premixed flames?

(from Sadasivuni et al., ASME GT2012-68483)

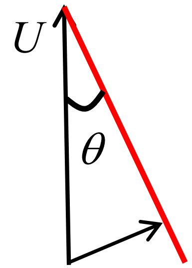








Note: Flame propagates in local normal direction – Huygen principle



$U \sin\theta = S_L$ - laminar flame speed or burning velocity

Important point to note

$$\frac{\partial \rho Y_i}{\partial t} + \frac{\partial \rho U Y_i}{\partial x} = \frac{\partial}{\partial x}\left(\rho \mathcal{D} \frac{\partial Y_i}{\partial x}\right) + w_i$$

$$\frac{\partial \rho Y_i}{\partial t} = w_i$$

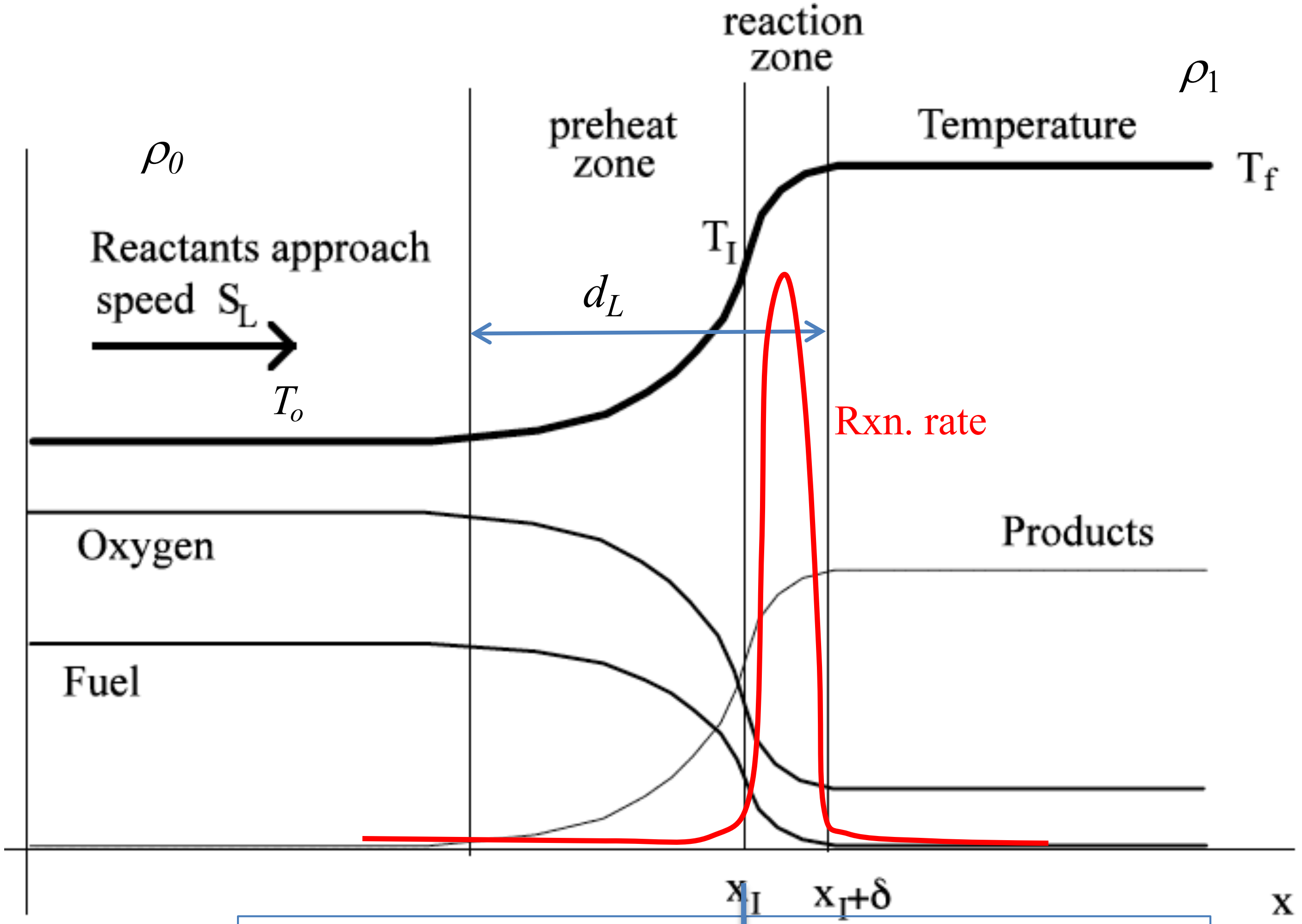
For limit phenomena

For flames – spatial terms must be retained in analysis

Assumptions

- p is constant
- Molecular weights, λ and c_p are constant
- Adiabatic flow
- Steady flow
- One step chemistry
- Unity Lewis number

Typical flame structure



Convection = diffusion | Reaction = diffusion

Mallard & Le Chatlier Analysis:

S_L is Eigenvalue

Final result – laminar burning velocity

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$$S_L \approx \sqrt{2A \, \frac{MW_{fu}}{MW_{fu}\, MW_{ox}} \left(\frac{\lambda}{\rho_0 c_p}\right) \frac{\rho_1^2}{\rho_0} \frac{Y_{fu,0}}{(T_f - T_0)^3} \left(\frac{R^0 T_f^2}{E}\right)^3 \exp\left(-\frac{E}{R^0 T_f}\right)}$$

Trends?
Lect. notes
p. Ch6/7 & 8

Flame thickness:

$$d_L = \frac{\lambda / \rho_0 c_p}{S_L}$$

Chemical time:

$$\tau_{chem} = \frac{d_L}{S_L} = \frac{\lambda / \rho_0 c_p}{S_L^{\ 2}}$$

Experimental data for burning velocity

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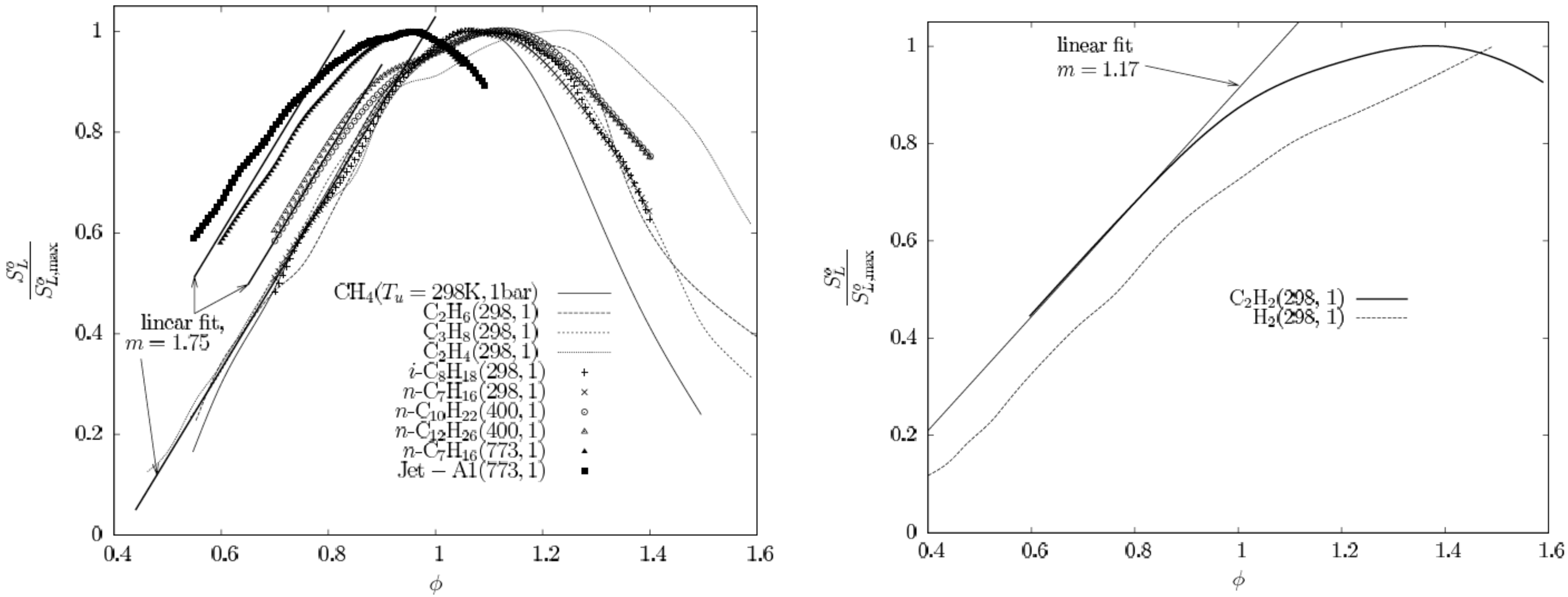
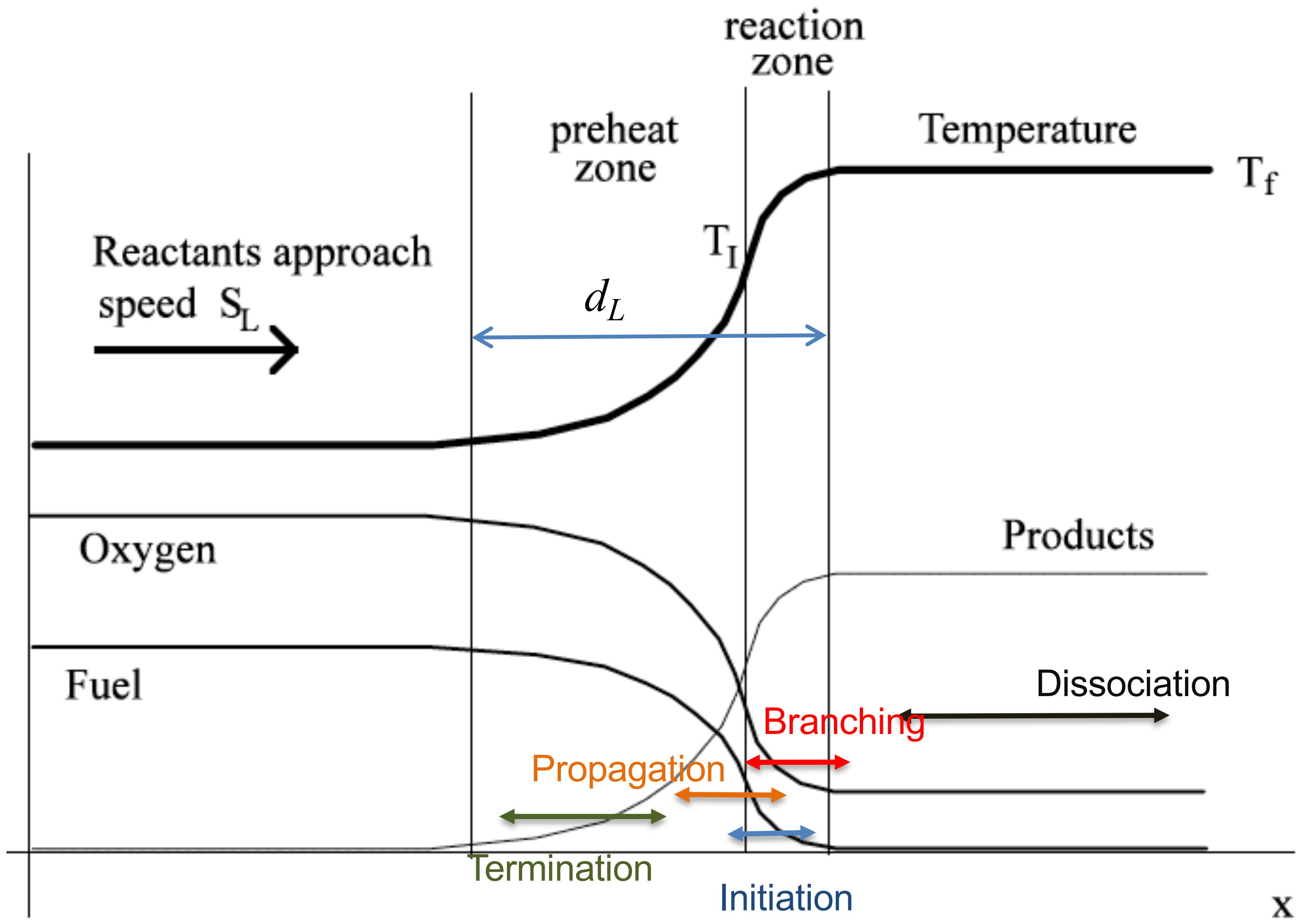


Figure 1.2: Variation of laminar flame speed with equivalence ratio for commonly used hydrocarbon–air mixtures. The flame speed is normalised by its maximum value, $S_{L,\max}^o$, which is [15] 0.416 m/s, 0.433, 0.449, 0.722, [16] 0.352, 0.405, [17] 0.658, 0.682, [18] 2.312 and 2.023 in the same order as in the legend. For acetylene– and hydrogen–air mixtures [15] it is 1.559 m/s and 2.856 respectively.

(taken from Turbulent Premixed Flames,
N. Swaminathan & KNC. Bray (Eds.), CUP, 2011)

Multi-step & Flammability limits



Simple theory for quenching distance

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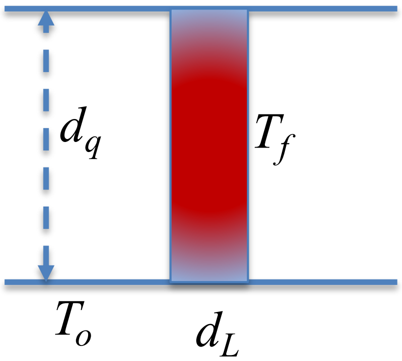

$$\omega_f Q \frac{\pi d_q^2}{4} d_L \sim \lambda \frac{(T_f - T_o)}{(d_q/2)} \pi d_q d_L$$

$$\frac{\rho_o S_L}{d_L} \qquad C_p(T_f - T_o)$$

$$\Longrightarrow d_q \sim d_L$$

From experiments: $d_q = 2d_L$

Summary

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- Preheat zone and reaction zone
- An approximate theory for laminar burning velocity – contains all important trends
- Estimates of flame thickness and reaction time
- The burning velocity peaks around stoichiometry and drops on either side
- Flammability limits – range of equivalence ratio where flame propagation is possible – chemical effects
- Ignition kernel should have size about flame thickness to initiate flame & quenching distance is about 2*flame thickness

Next: Non-premixed flames