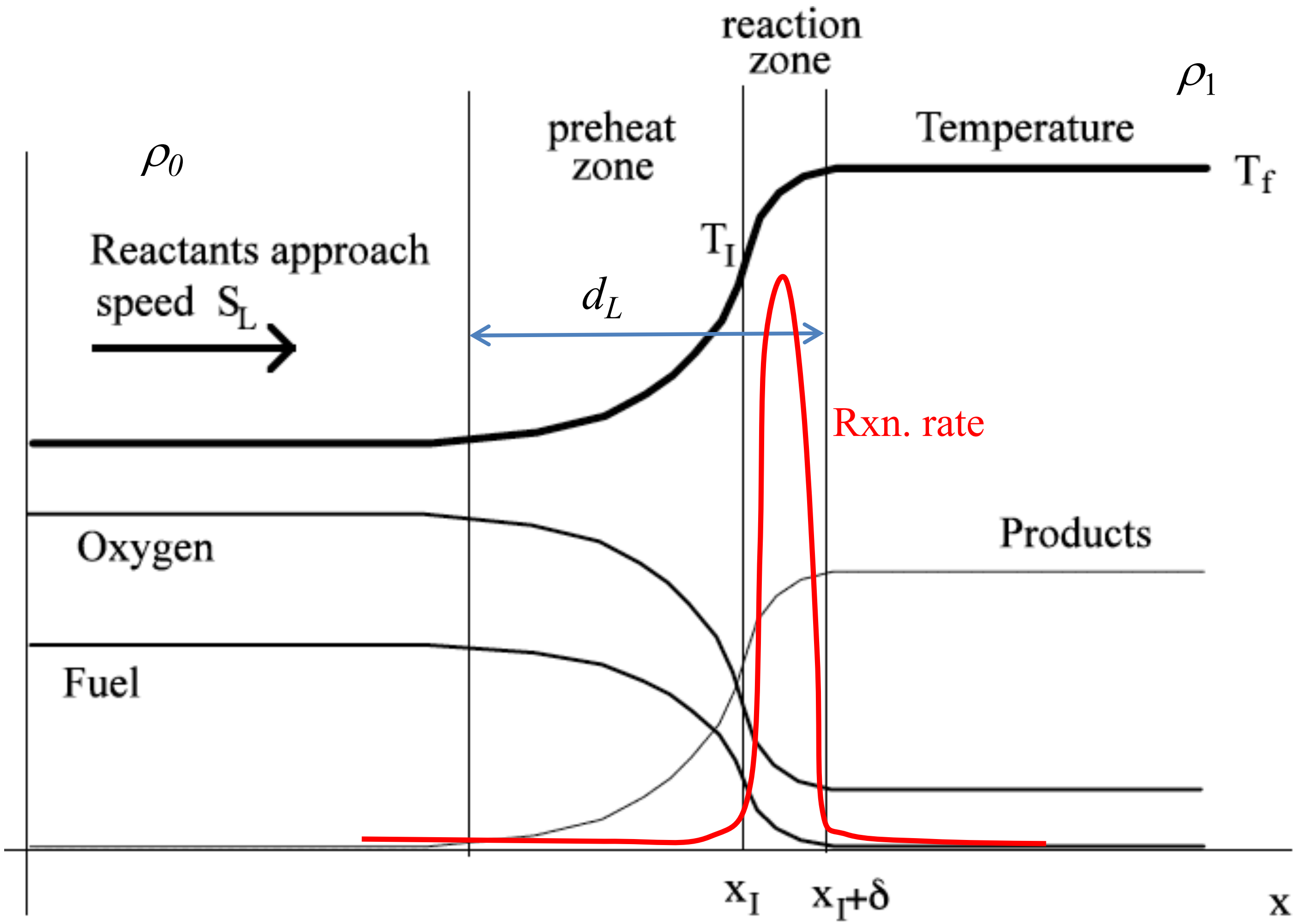
Lecture 7:

Ch. 7: Laminar non-premixed flames & droplet combustion

Typical premixed flame structure - Revist



S_L is Eigenvalue

Recap

- An approximate theory for laminar burning velocity – contains all important trends
- 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

Premixed & Non-premixed Flames

Premixed flame

Diffusion flame

F, O | Product

Ex. Spark ignition engines
Stationary GT
a variant for future Aero-GT

F | O

Ex. CI engines
Furnaces, Old GTs
Current Aero-GT, after burners
In modern terms – a "dirty flame"

Objective – Non-premixed Flames

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- Practical applications
- Structure of non-premixed flames
- Present a elementary theory
- Droplet evaporation time
- Other aspects of non-premixed flames

Why study? – A practical perspective

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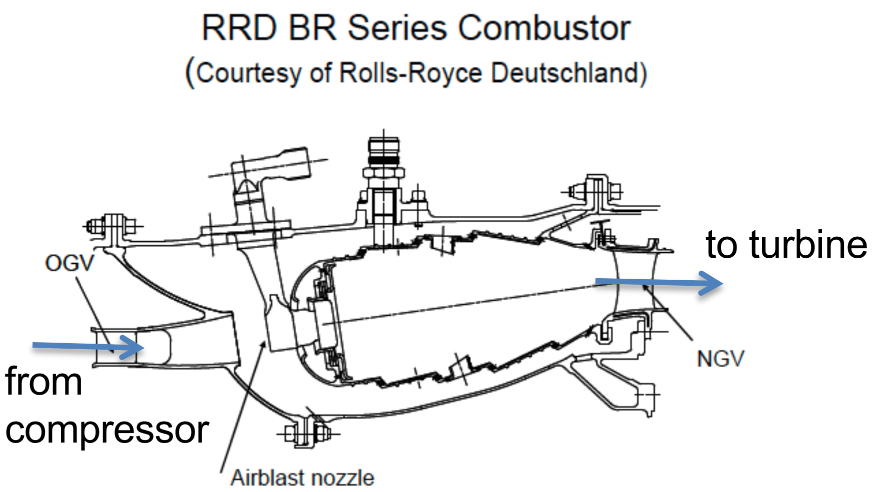

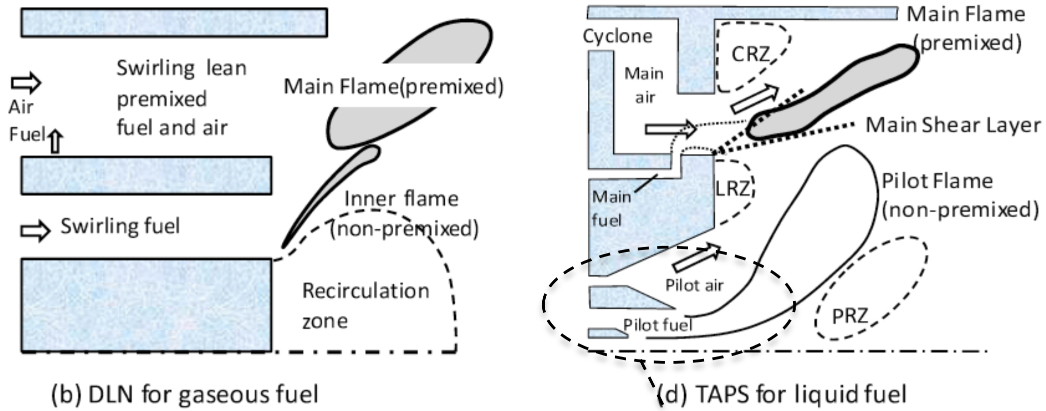

(taken from Turbulent Premixed Flames, N. Swaminathan & KNC. Bray (Eds.), CUP, 2011)

Figure 7.1 in the notes

- Liquid fuels – usually burn in non-premixed mode
- Diesel engines, Aero gas turbines, industrial burners, coal combustion – few examples
- In modern terms – dirty flames, an alternative is partially premixed combustion – a hot current research topic!
- must understand non-premixed combustion, a simple theory for it

Flame structure - Difference

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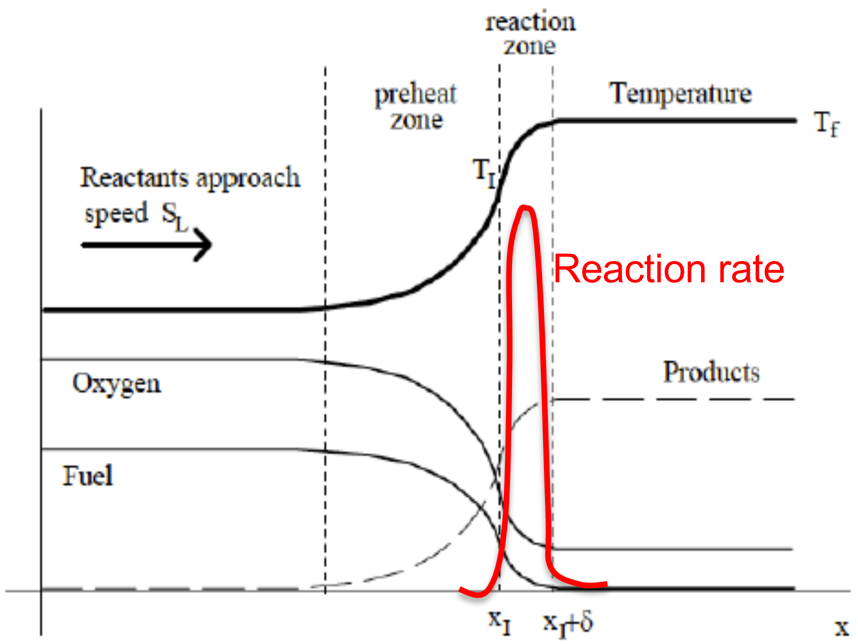
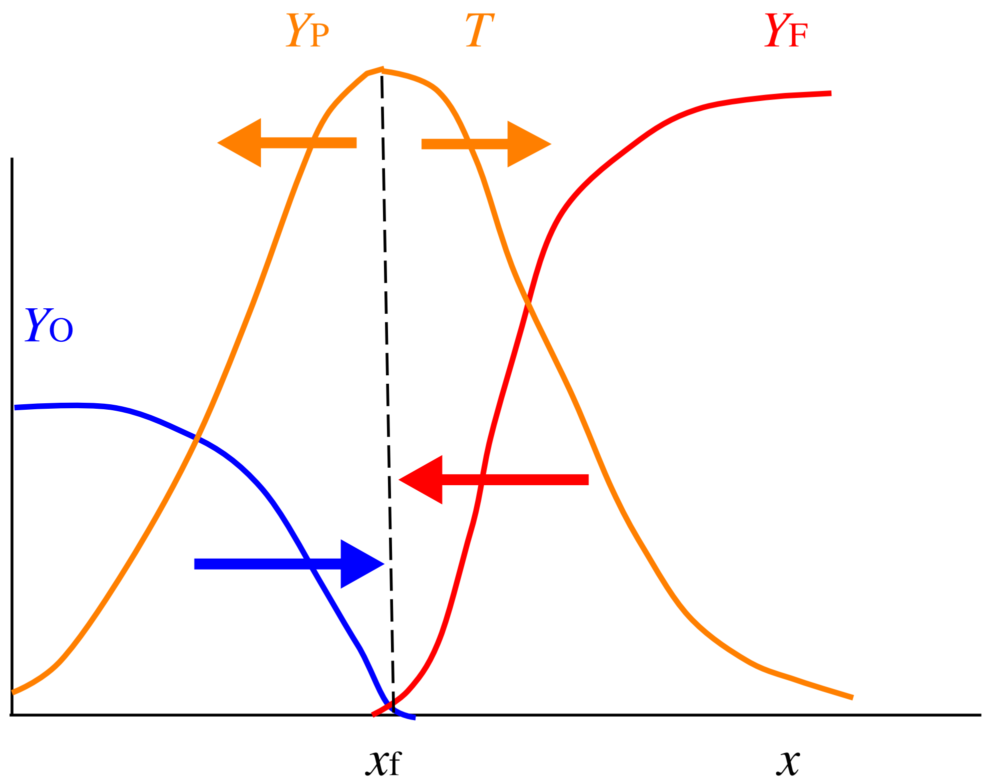


Premixed

There is propagation



Non-Premixed

No propagation

Formulation

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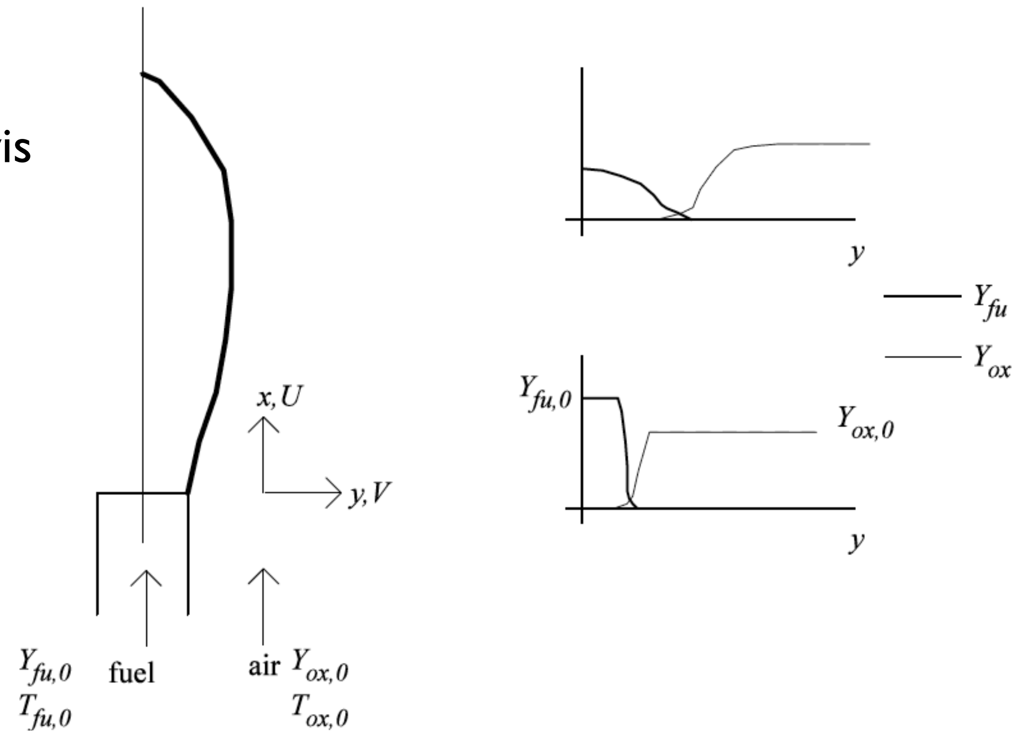
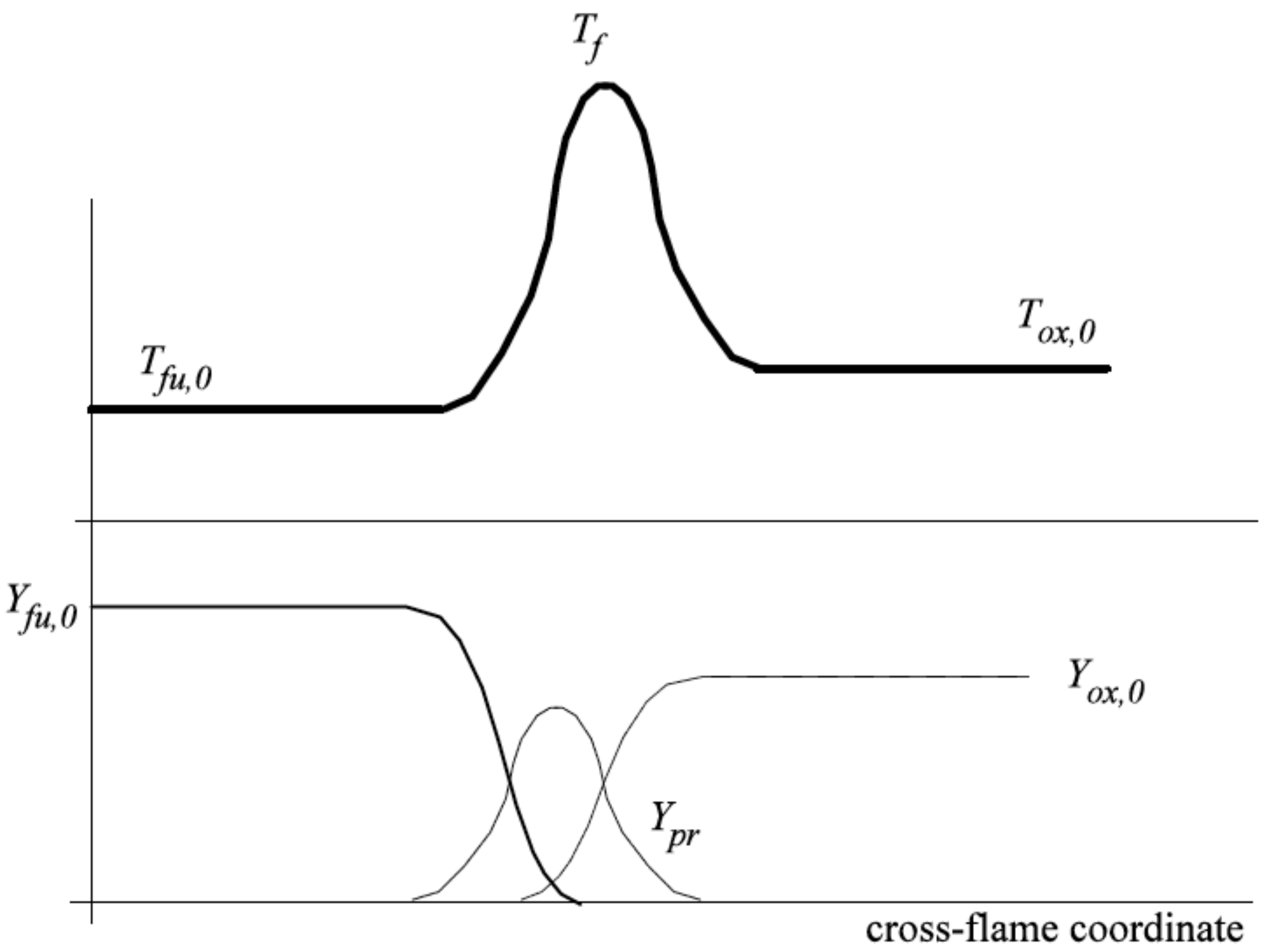
Assumptions:

- p is constant & adiabatic flow
- Steady flow, constant c_p, λ, unity Lewis number
- One step chemistry



- Momentum conservation
- Mass conservation
  - Fuel, oxidiser, (product)
- Energy conservation
- Ideal gas equation - density

Typical variation – B.C.s



Mixture fraction

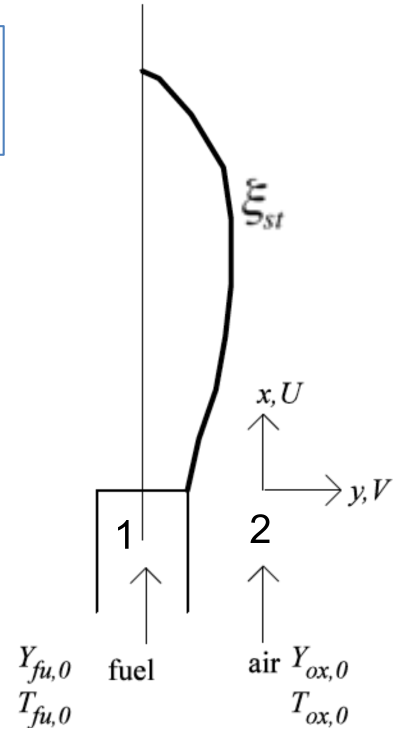
Z, conserved scalar – from Lect. 4 – Schvab-Zel'dovich coupling functions:

$$Z_1 = Y_{fu}Q + c_pT \qquad Z_2 = Y_{ox}Q + Sc_pT \qquad Z_3 = Y_{fu} - Y_{ox}/S$$

Mixture fraction:

$$\xi = \frac{(Y_{fu} - Y_{ox}/S) - (Y_{fu} - Y_{ox}/S)_2}{(Y_{fu} - Y_{ox}/S)_1 - (Y_{fu} - Y_{ox}/S)_2} = \frac{Z_3 - Z_{3,2}}{Z_{3,1} - Z_{3,2}}$$

$$\boxed{\phi = \frac{\xi(1-\xi_{st})}{\xi_{st}(1-\xi)}}$$



Pure fuel stream: $Z_{3,1} = Y_{fu,1} = 1$ Oxidiser stream: $Z_{3,2} = Y_{ox,2} = 0.233$

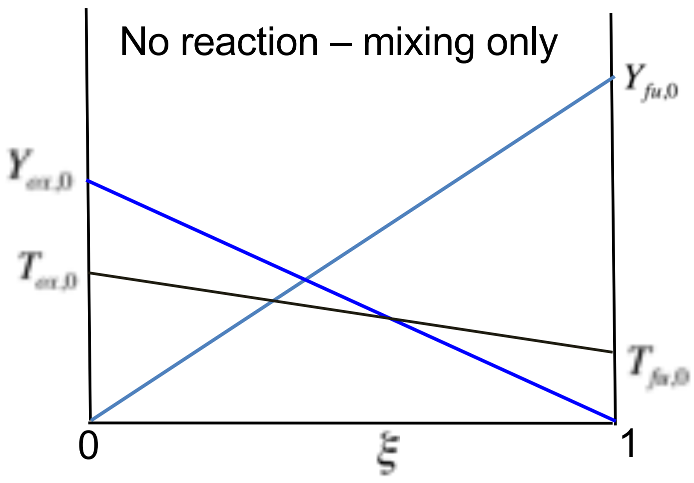
$$\xi_{st} = \frac{Y_{ox,2}/S}{Y_{fu,1} + Y_{ox,2}/S}$$

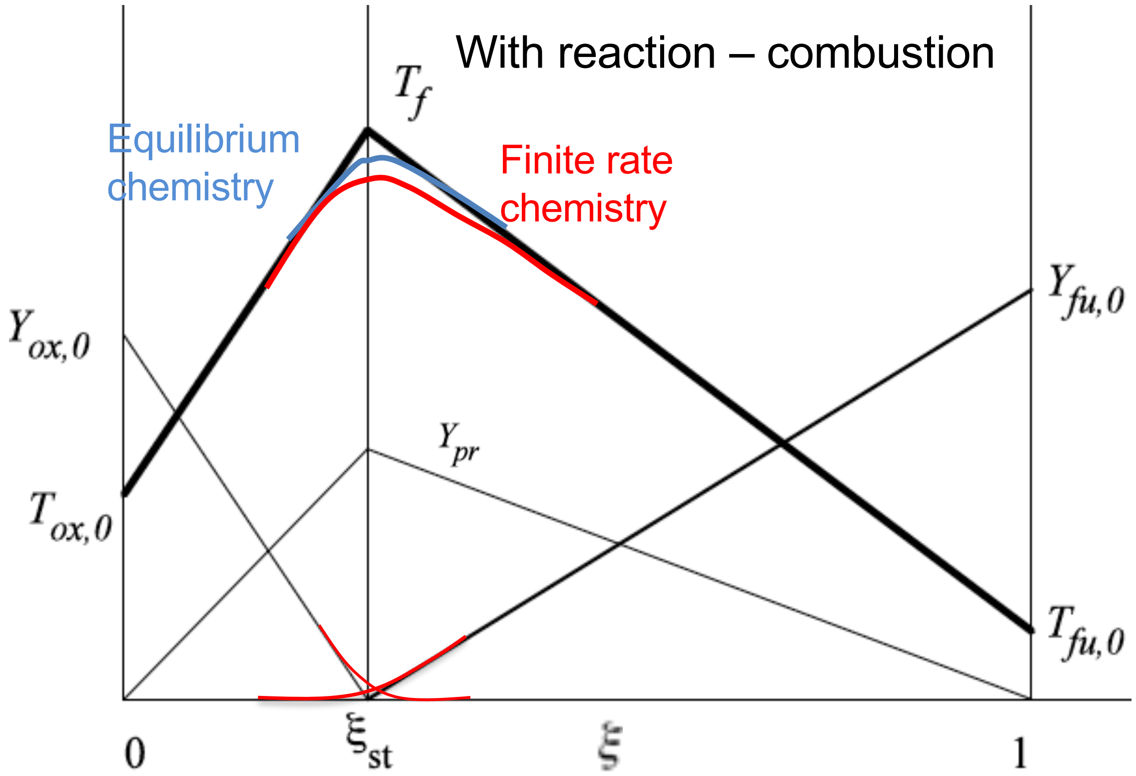
for CH4-air combustion: $S = 2 \times 31.999/16.043 = 3.989$

$\xi_{st} = 0.0552$

Physical meaning of ξ?

State relationship





This is mixture fraction approach

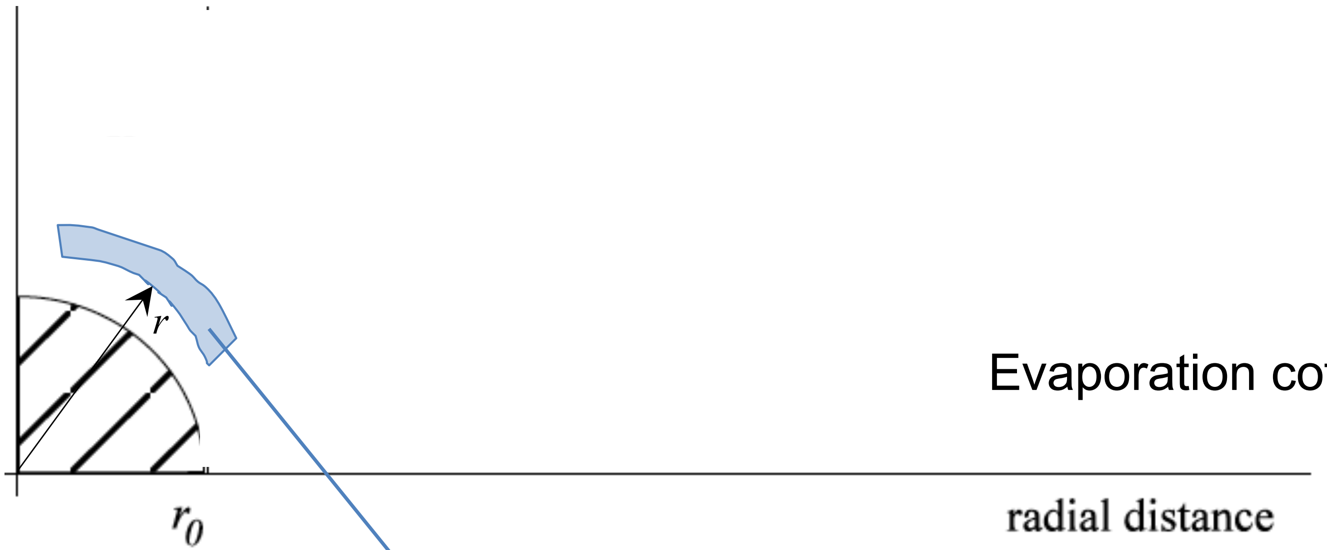
This is known as flame-sheet model – assumes infinitely fast reaction

Known as diffusion or mixing controlled

This can be used for any types of flows

How about finite rate chemistry/reaction? – red lines in the above diagram

Droplet evaporation



$$4\pi r^2 \rho U = \text{constant} = 4\pi r_0^2 \rho_0 U_0 = 4\pi r_0^2 \dot{m}''_{fu,0}$$

$$\frac{dm_d}{dt} = -\dot{m}_{fu}$$

$$\frac{d}{dr}\left(r^2 \dot{m}''_{fu}\right) = 0 \Leftrightarrow \quad \frac{d}{dr}\left[r^2\left(Y_{fu}\rho U - \rho D \frac{dY_{fu}}{dr}\right)\right] = 0$$

$$\rho_L \frac{dr_0}{dt} = -\dot{m}''_{fu,0}$$

$$r^2 \rho D \frac{dY_{fu}}{dr} = r_0^2 \dot{m}''_{fu,0}(Y_{fu} - 1)$$

$$\dot{m}''_{fu,0} = \frac{\rho D}{r_0} \ln\left(\frac{1 - Y_{fu,\infty}}{1 - Y_{fu,0}}\right)$$

Transfer number

$$B = \frac{Y_{fu,0} - Y_{fu,\infty}}{1 - Y_{fu,0}}$$

Evaporation cof. (m^2/s)

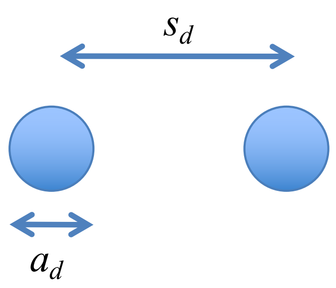
$$\beta = 8 \frac{\rho D}{\rho_L} \ln(1 + B)$$

$$\boxed{d_{in}^{\,2} - d^2 = \beta \; t}$$

$$\boxed{t_{vap} = \frac{\rho_L}{8 \rho D \ln(1 + B)} d_{in}^{\,2}}$$

Trends?

Droplet Combustion



$$G = 3\left(1 + 0.276\mathrm{Re}_d^{1/2}\mathrm{Sc}^{1/3}\right)\mathrm{Le}N^{2/3}(a_d/s_d)$$

N – number of droplets

$G < 1$ – individual droplet combustion

$G > 1$ – sheath (group) combustion

Individual or group combustion?

Neophytou et al.
Combust. Flame,
159, p.641-664, 2012

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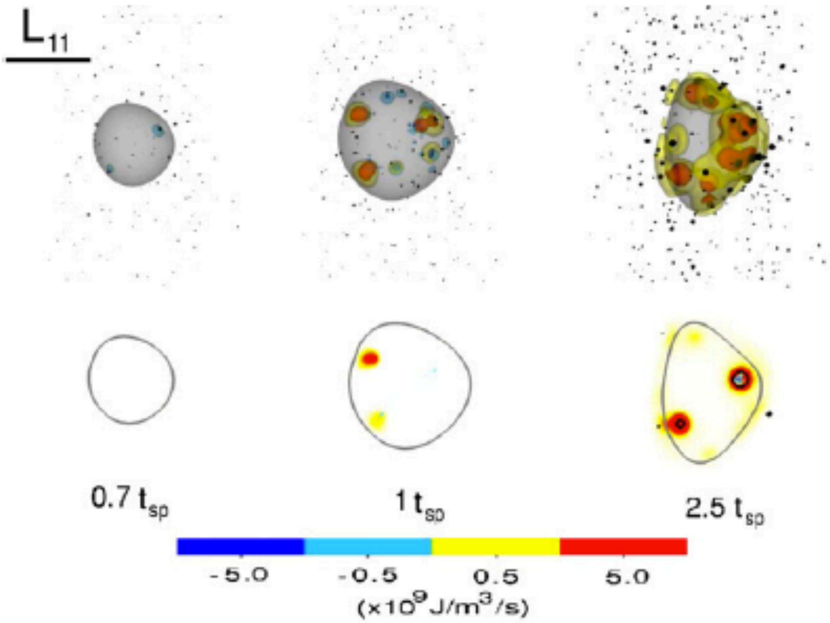
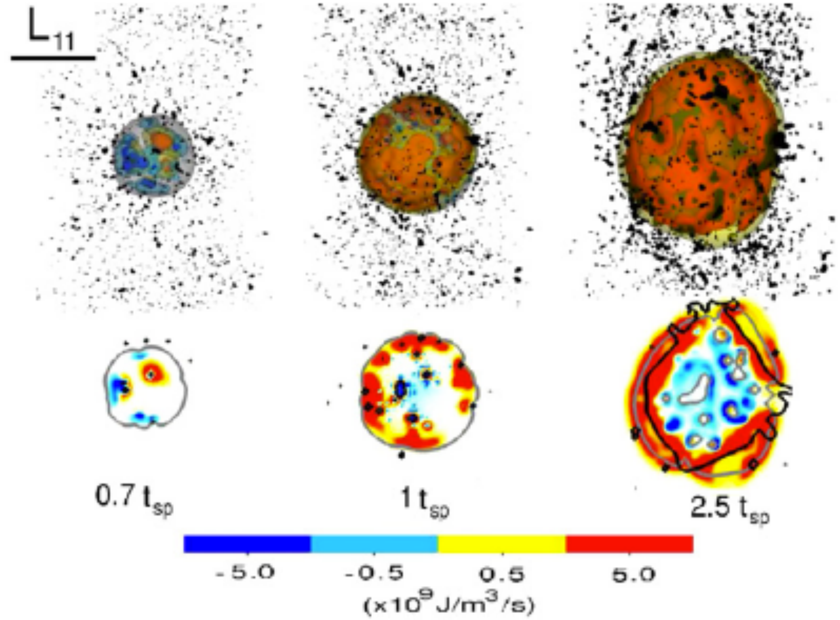
3D

2D slice



(a)

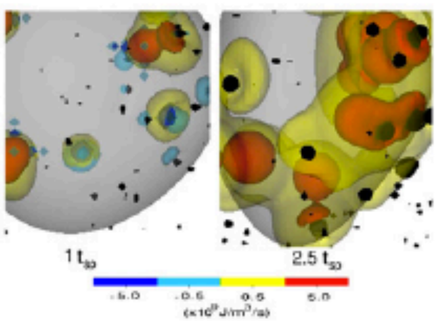
G ~ 2



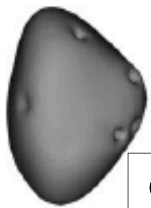
(a)

G ~ 20

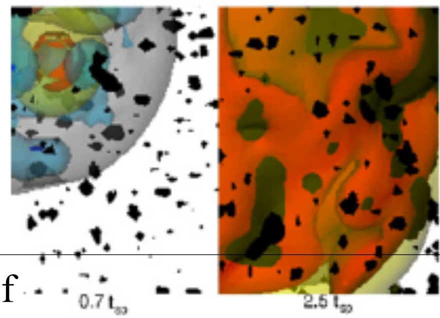
Magnified views



(b)



(c)



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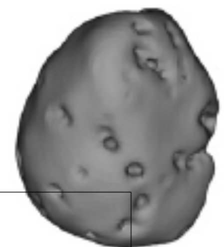

(c)

Grey – iso-surface of
T = 1400K,
Black – ξ_{st} iso-surface, approximately these are droplet locations

Summary

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- Fuel and oxidiser are supplied from different sides of a non-premixed flame
- Flame is located at the interface where the mixture is stoichiometric and there is no flame propagation
- Rxn. rate is faster than molecular diffusion – diffusion limited/controlled combustion
- Flame sheet model is introduced
- Liquid fuel droplets need to be evaporated before combustion can occur – an expression for evaporation time
- $t_{\mathrm{evap}} \downarrow \quad d_{in} \downarrow; \qquad D \uparrow; \qquad B \uparrow$
- B – driving potential for mass transfer
- Individual or group combustion – Group number, G, (dia./inter dist.)

Next

Ch. 8: Pollution from combustion
&
Turbulent Combustion (only a brief intro.)

http://to.eng.cam.ac.uk/teaching/surveys/4A13_Lent.html