Lecture 9.
Turbulent Non-premixed Flames (TNF)

Content

- TNF – engineering applications
- Structure of TNF
- Scales and non-dimensional numbers
- Regimes of turbulent diffusion flames
- Flame/eddy interaction
- Flame location, shape and flame height

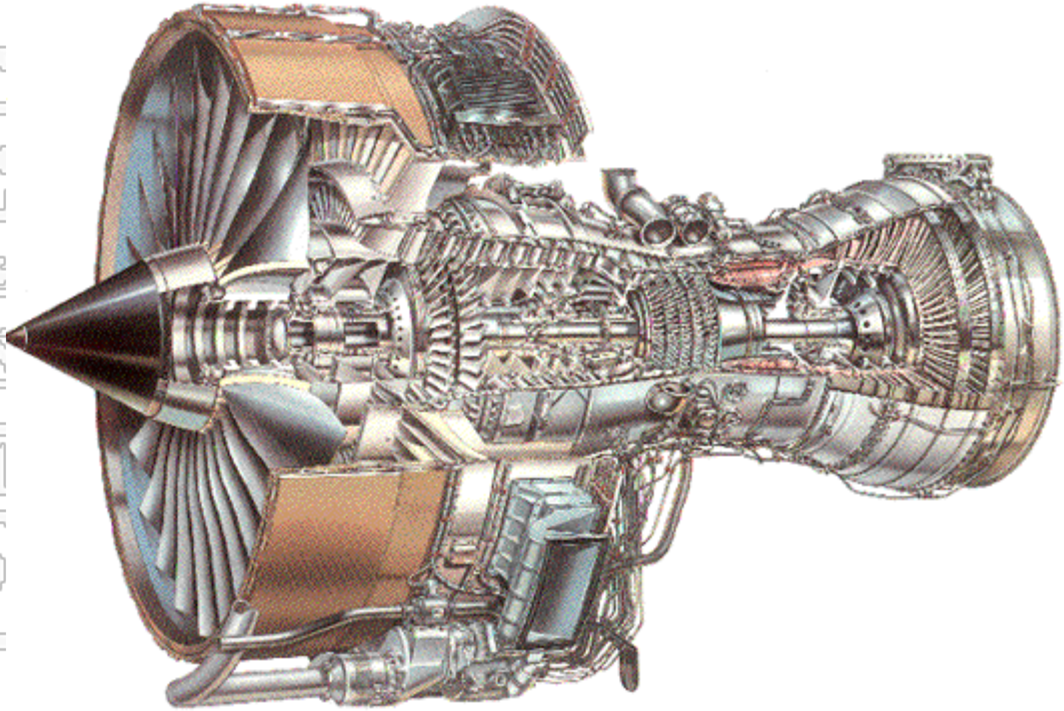
TNF – engineering applications

Space shuttle

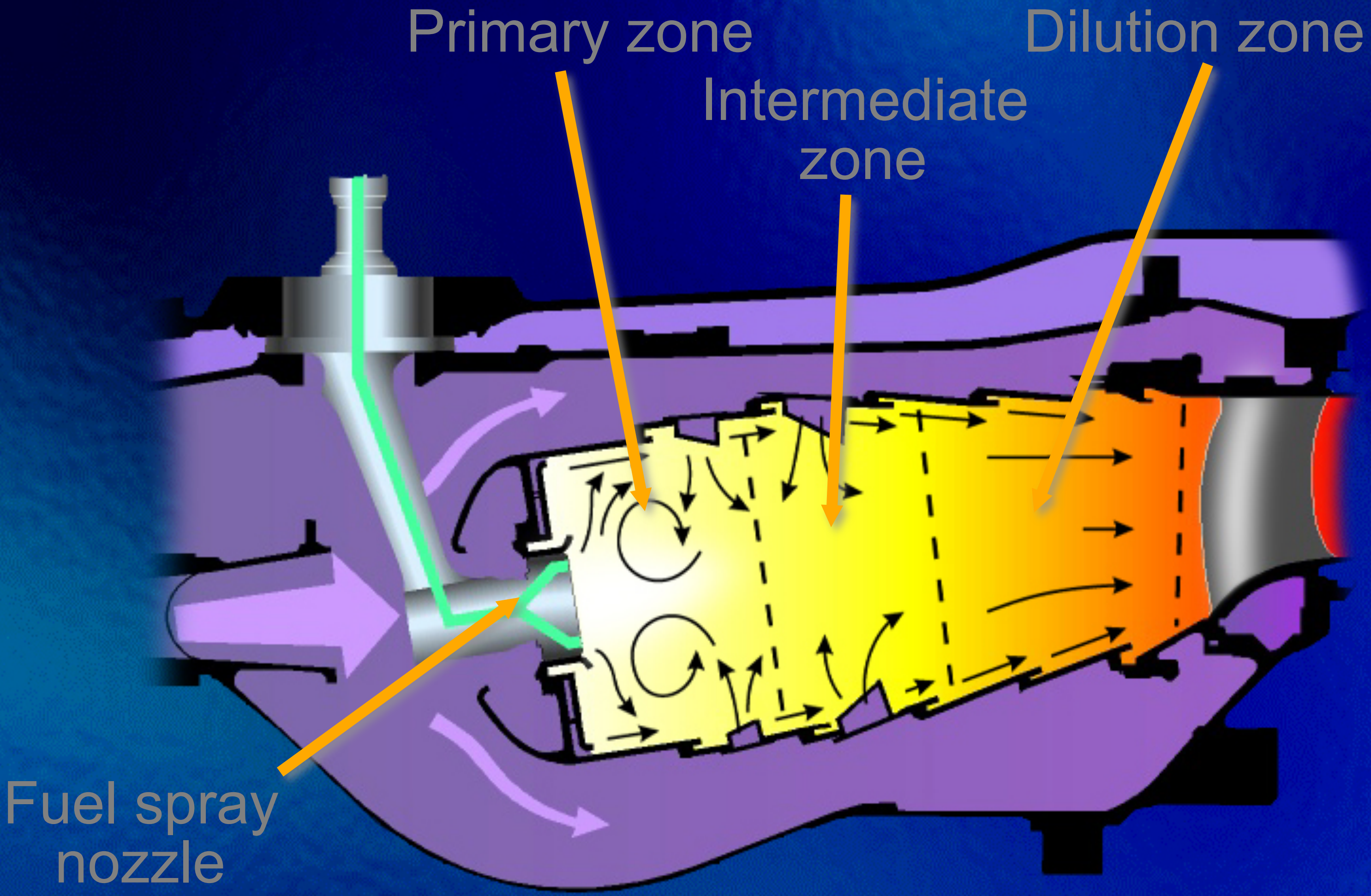
TNF
in rocket
engines

Airbus A380 engine

Rolls Royce Trent 900

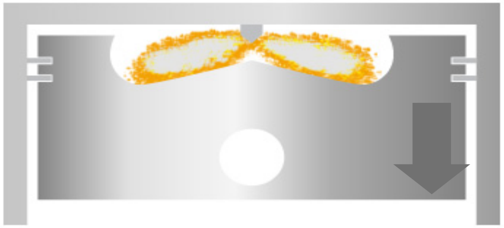


Combustor Operation

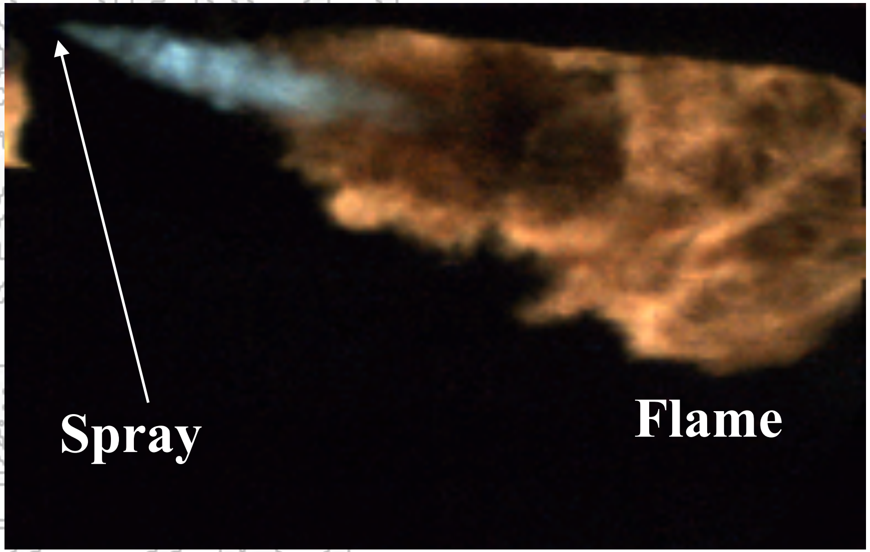


Rolls-Royce

Compression ignited engine (Diesel combustion)



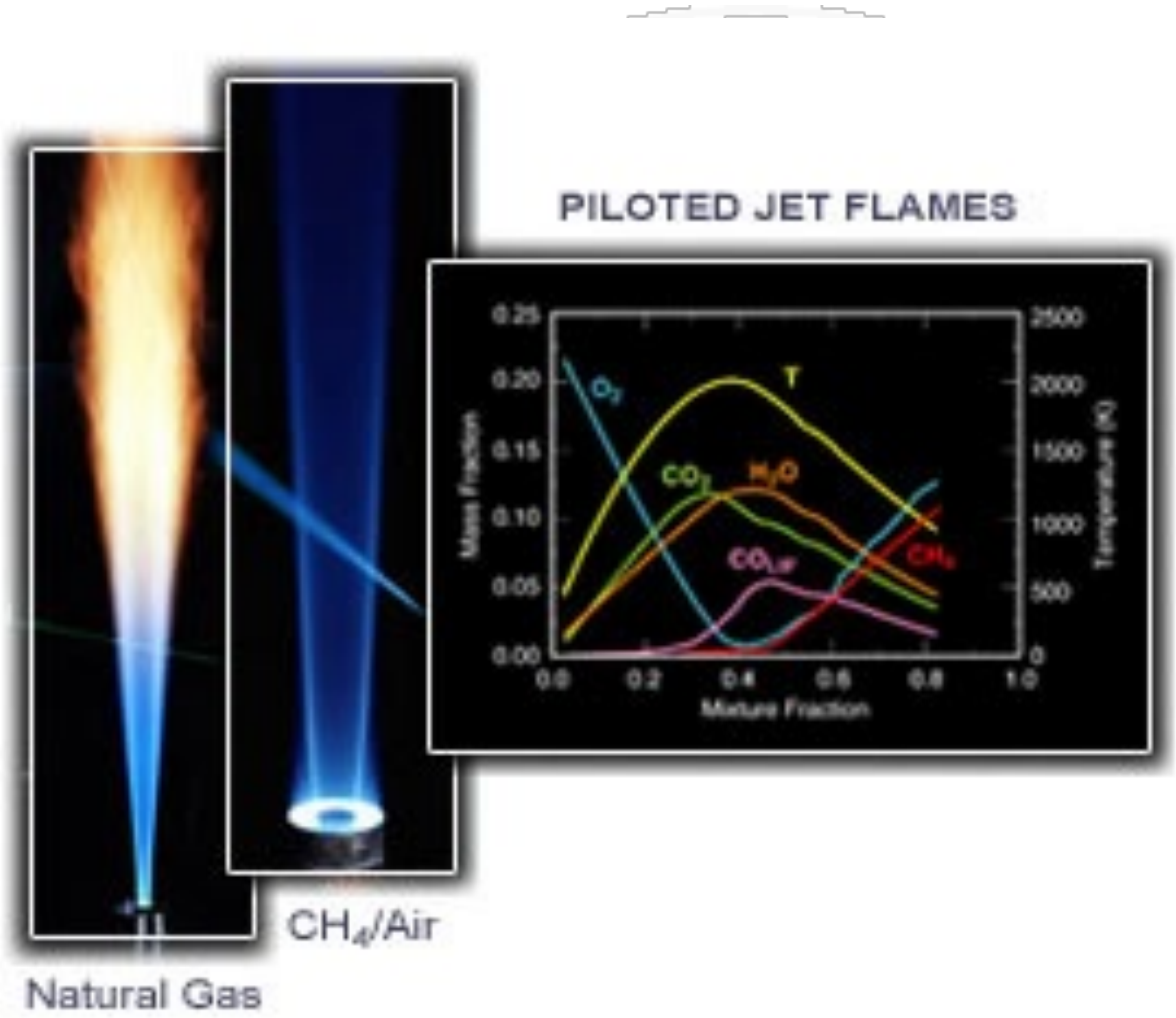
- Combustion during injection
- Diffusion flame
- Yellow flame (=soot)
- Local lambda ~1
- Overall lambda ~1,5 (no three-way cat)

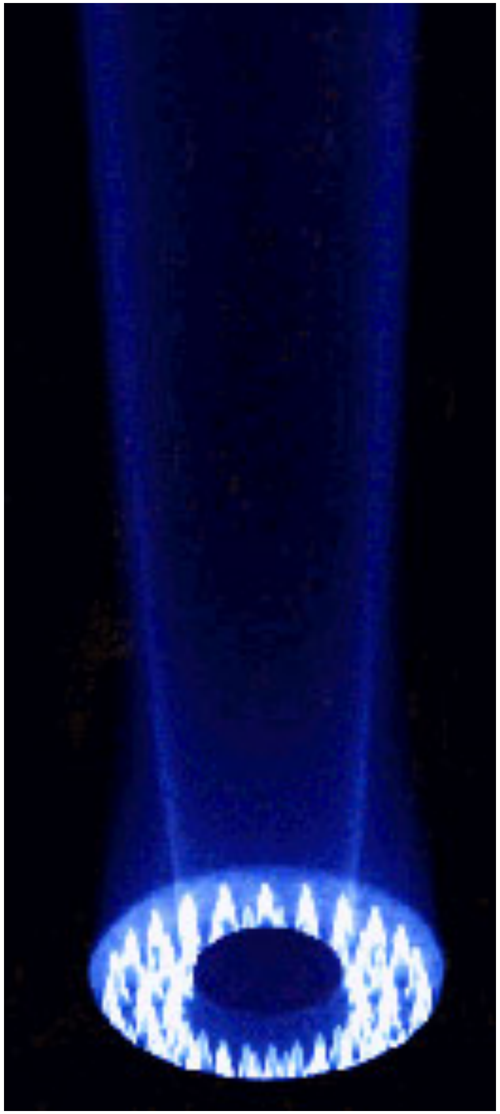


Diffusion flame in Scania 14-liters engine.
Foto: Anders Larsson, Scania

TNF – experimental observations

Piloted jet flame: Sandia, Delft TU, TU Darmstadt, TNF workshop

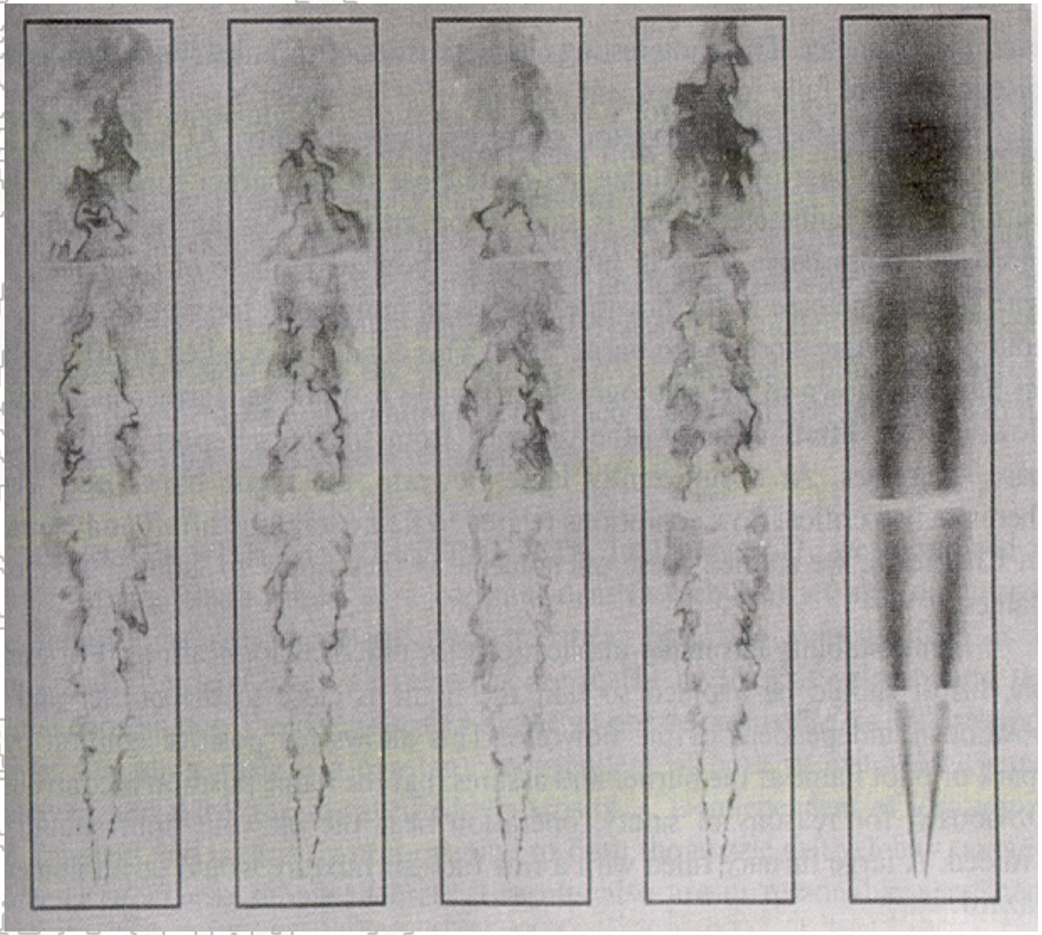




OH radicals in TNF

- Turbulent jet diffusion flame

- OH radical
- instantaneous (left 4)
- mean (right)



Features of TNF

- The instantaneous OH is found in a rather **thin zone**, especially at the bottom of the figure close to the jet inlet. We can understand this from the laminar flame structures: OH is mostly found in the reaction zone. The reaction zone is very thin.

- The instantaneous OH zone is highly wrinkled, i.e. the turbulent non-premixed flame is also highly **wrinkled**. This is due to the influence of turbulence eddies that are randomly moving in the flow field;

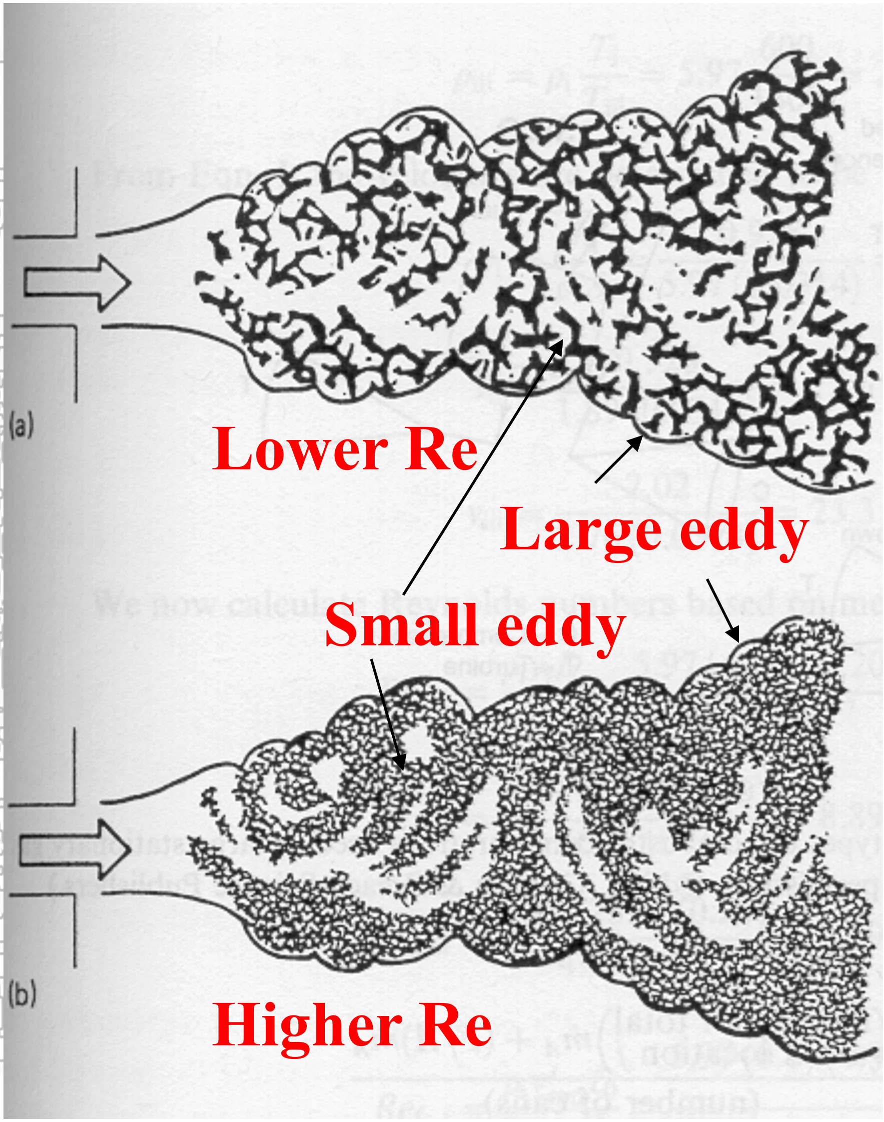
- At the tip of the flame (upper part of the figure) the OH is found in rather thick zone. This is likely due to the **'history' effect** – namely, even if the OH is produced in a rather thin zone, the OH will still be accumulated at the tip of the flame;

- Finally, we observe that the time averaged OH is found in a thicker zone and the zone is rather smooth (no wrinkling). We will call this phenomenon **'flame broadening by turbulence'**.

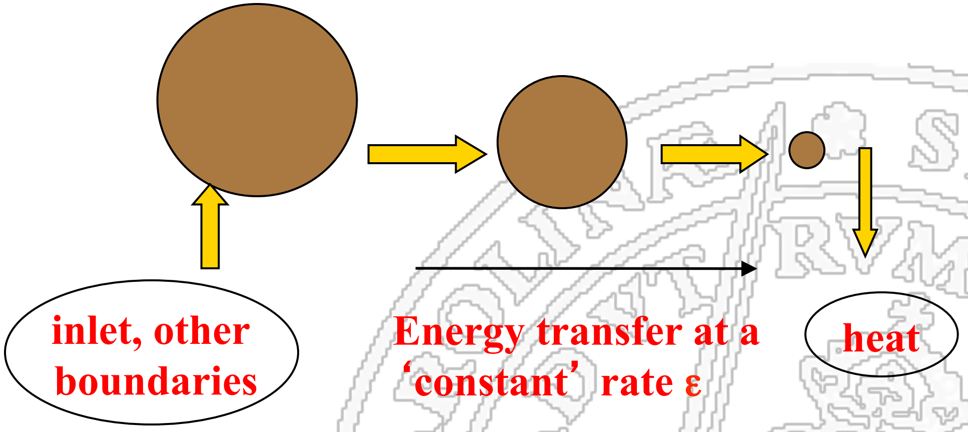
Flame/turbulence interaction

Different scales in turbulent premixed flames

- Flow scales
  - Mean flow scales
    - Length (L),
    - velocity (U),
    - time ($t=L/U$)
  - integral scales
    - length (l_0),
    - velocity ($u_0=u(l_0)$),
    - time ($t_0=l_0/u_0$),
  - Kolmogrov scales
    - length (l_k),
    - velocity ($u_k=u(l_k)$),
    - time ($t_k=l_k/u_k$),



Scale relationship



inlet, other boundaries

Energy transfer at a 'constant' rate ε

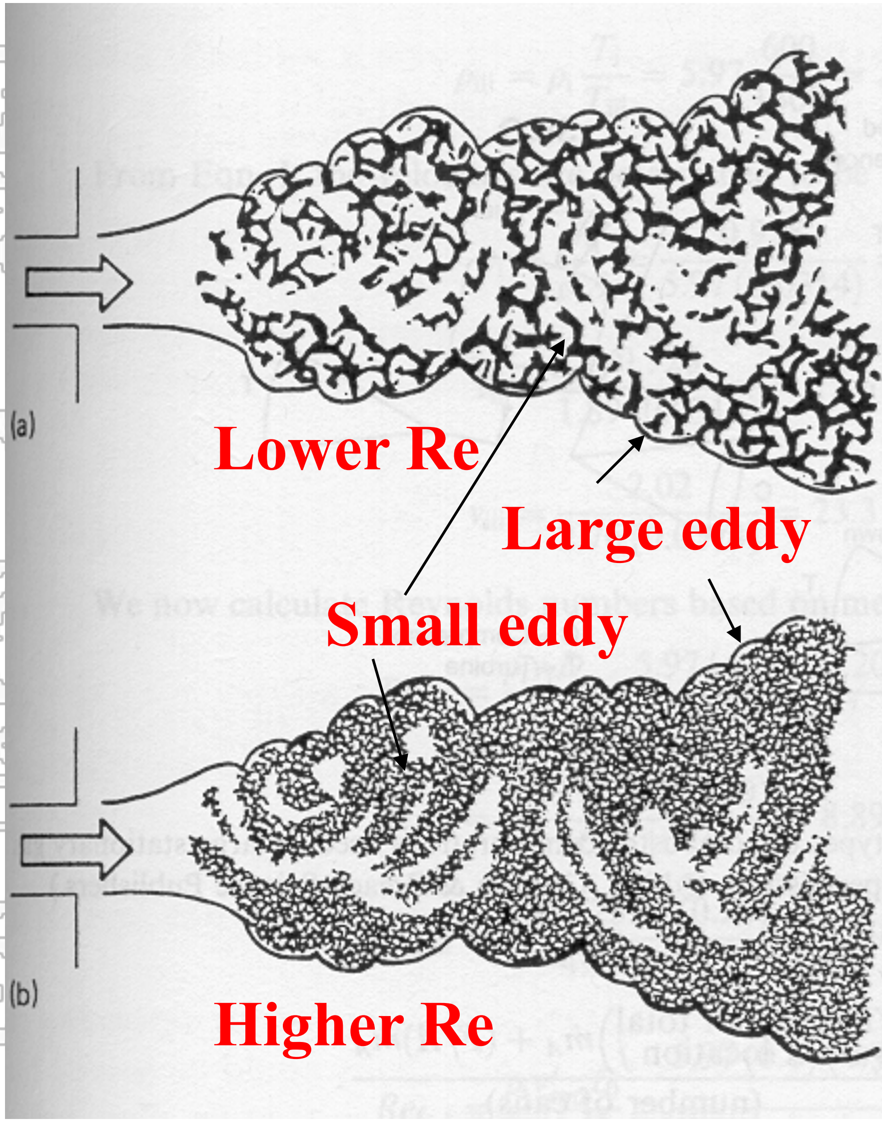
heat

$$\varepsilon \propto \frac{u_0^3}{l_0} \propto \frac{u_k^3}{l_k} \Rightarrow \frac{t_0}{t_k} \propto \frac{l_0}{u_0}\frac{u_k}{l_k} \propto \left(\frac{l_0}{l_k}\right)^{2/3}$$

$$\frac{u_k l_k}{\nu} \propto 1 \Rightarrow \frac{u_0 l_0}{u_k l_k} \propto \mathrm{Re}_l$$

$$\frac{l_0}{l_k} \propto \frac{l_0}{l_k}\frac{u_0}{u_k}\frac{u_k}{u_0} \propto \frac{l_0 u_0}{\nu}\left(\frac{l_k}{l_0}\right)^{1/3}$$

$$\Rightarrow \frac{l_0}{l_k} \propto \mathrm{Re}_l^{3/4}; \frac{u_0}{u_k} \propto \mathrm{Re}_l^{1/4}; \frac{t_0}{t_k} \propto \mathrm{Re}_l^{1/2};$$



Different scales in turbulent non-premixed flames

- Flow scales
  - integral scales
    - length (l_0), time (t_0), velocity (u_0),
    - fluctuation of Z near Z_{st}: $(Z')_{st}$
  - Kolmogrov scales
    - length (l_k), time (t_k), velocity (v_k)

- Flame scales
  - Flame thickness in physical space: δ_L
  - time scale ($t_c=1/\Omega$) = 1/chemical reaction rate
  - No velocity scale (no flame speed)

Turbulence mixing

- Mixing of large eddies
- Mixing of medium size eddies
- Mixing of Kolmogrov eddies

- Effective mixing rate of the entire flow

- Mixing of fuel and air eddies to the flame
  - Large eddies
  - Kolmogrov eddies
  - Mixing/reaction interaction

Physical interpretation of length, time and velocity scales

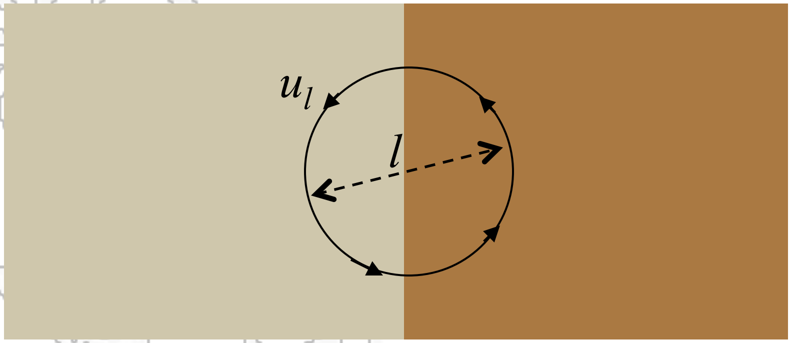
Turbulence eddy scales

Eddy size – l

Eddy velocity – u_l

Eddy turn over time – $t_{eddy} = l/u_l$

Molecular mixing time of
Material of size l – $t_{mixing} = l^2/D$



$$\frac{t_{eddy}}{t_{mixing}} = \frac{l}{u_l}\frac{D}{l^2} = \mathrm{Re}^{-1} \qquad \frac{t_k}{t_{mixing}} = \frac{l_k}{u_k}\frac{D}{l_k^2} = \mathrm{Re}_k^{-1} \propto 1$$

- Eddy turnover time is in general shorter than the molecular mixing time on the eddy length
- Kolmogorov eddy turnover time is the same as the mixing time of the Kolmogorov eddy length

Non-dimensional numbers in turbulent non-premixed flames

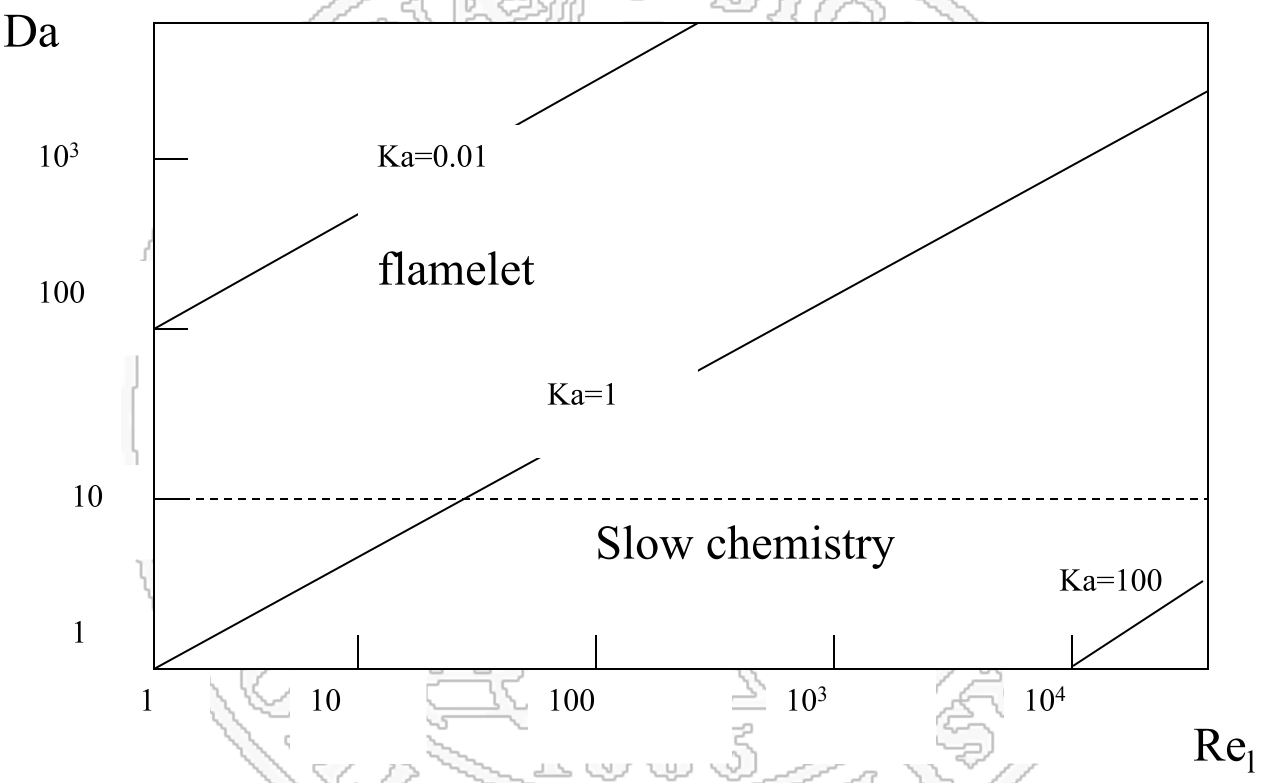
Reynolds number $$\mathrm{Re}_l = \frac{u_0 l_0}{\nu}$$

Damköhler number $$Da = \frac{t_0}{t_c}$$

Karlovitz number $$\mathrm{Ka} = \frac{t_c}{t_k} = \frac{t_c}{t_0}\frac{t_0}{t_k} = \mathrm{Da}^{-1}\,\mathrm{Re}_l^{1/2}$$

Turbulent intensity $$\left(Z'\right)_{st}$$

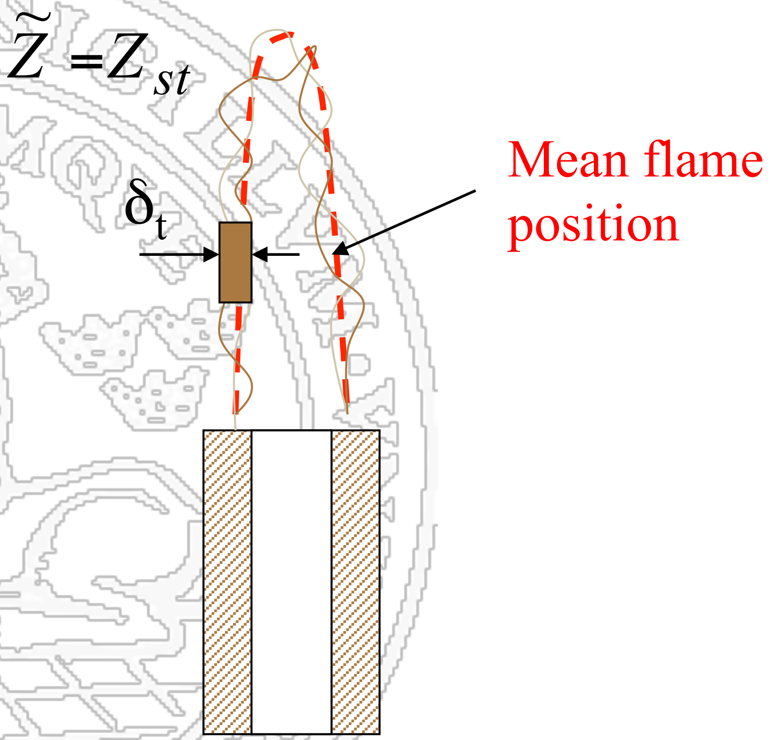
Regimes of TNF



Flamelet regime: ensemble averaged mean flames

Ensemble averaged mean flame

- Where is the flame?
  - The mean flame is at mean stoichiometric mixture fraction
  - Laminar flamelets fluctuate around the mean flame position within a thickness



OH radicals in TNF

- Turbulent jet diffusion flame

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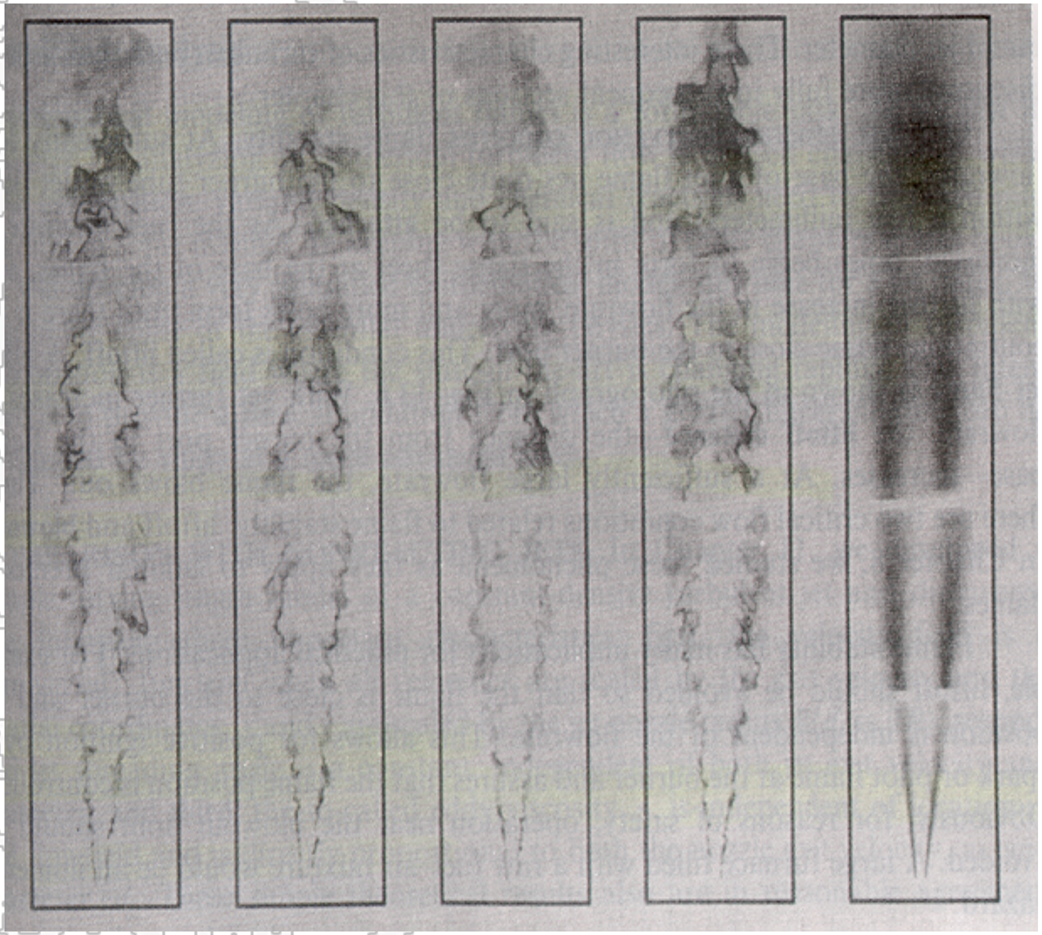
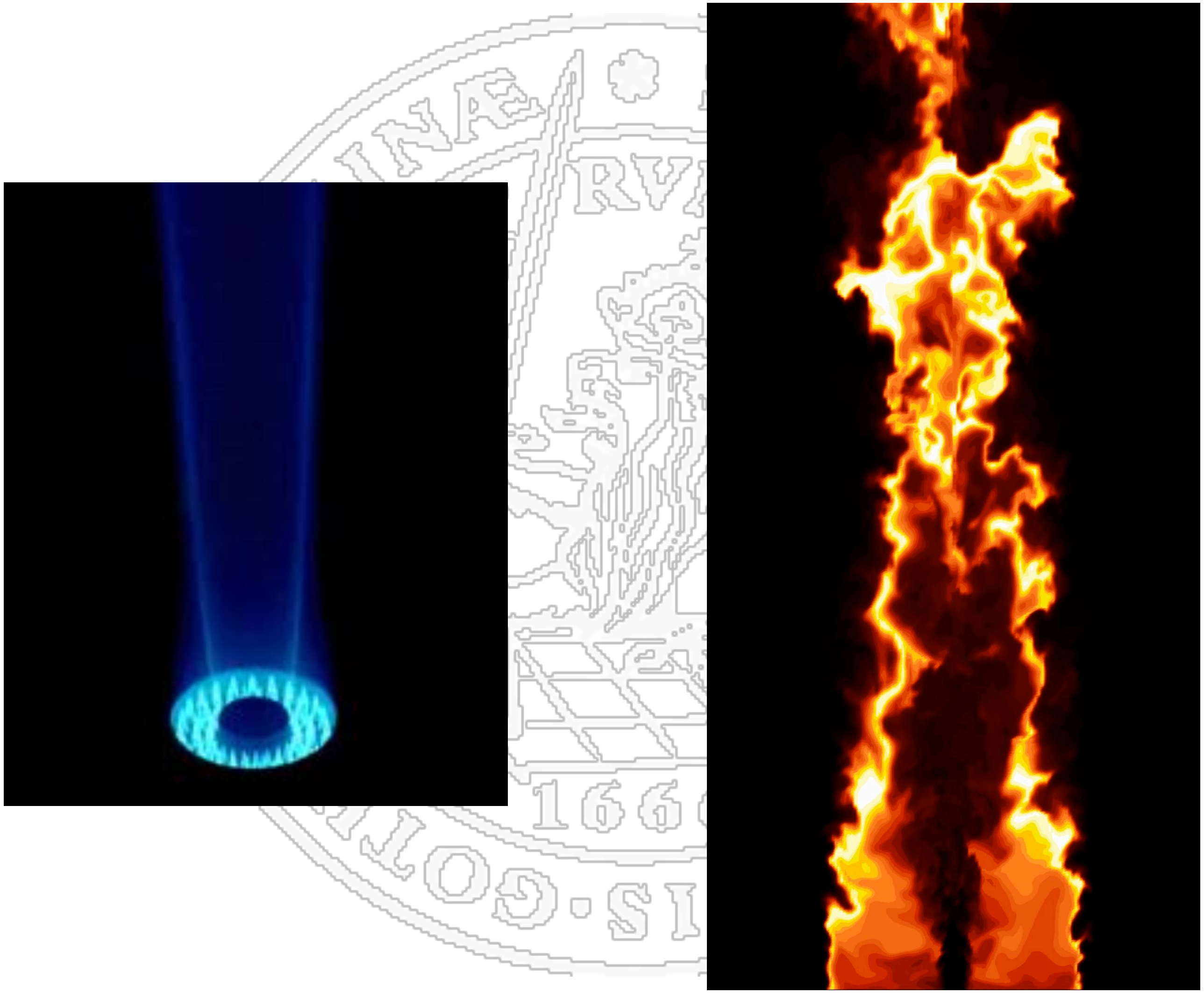
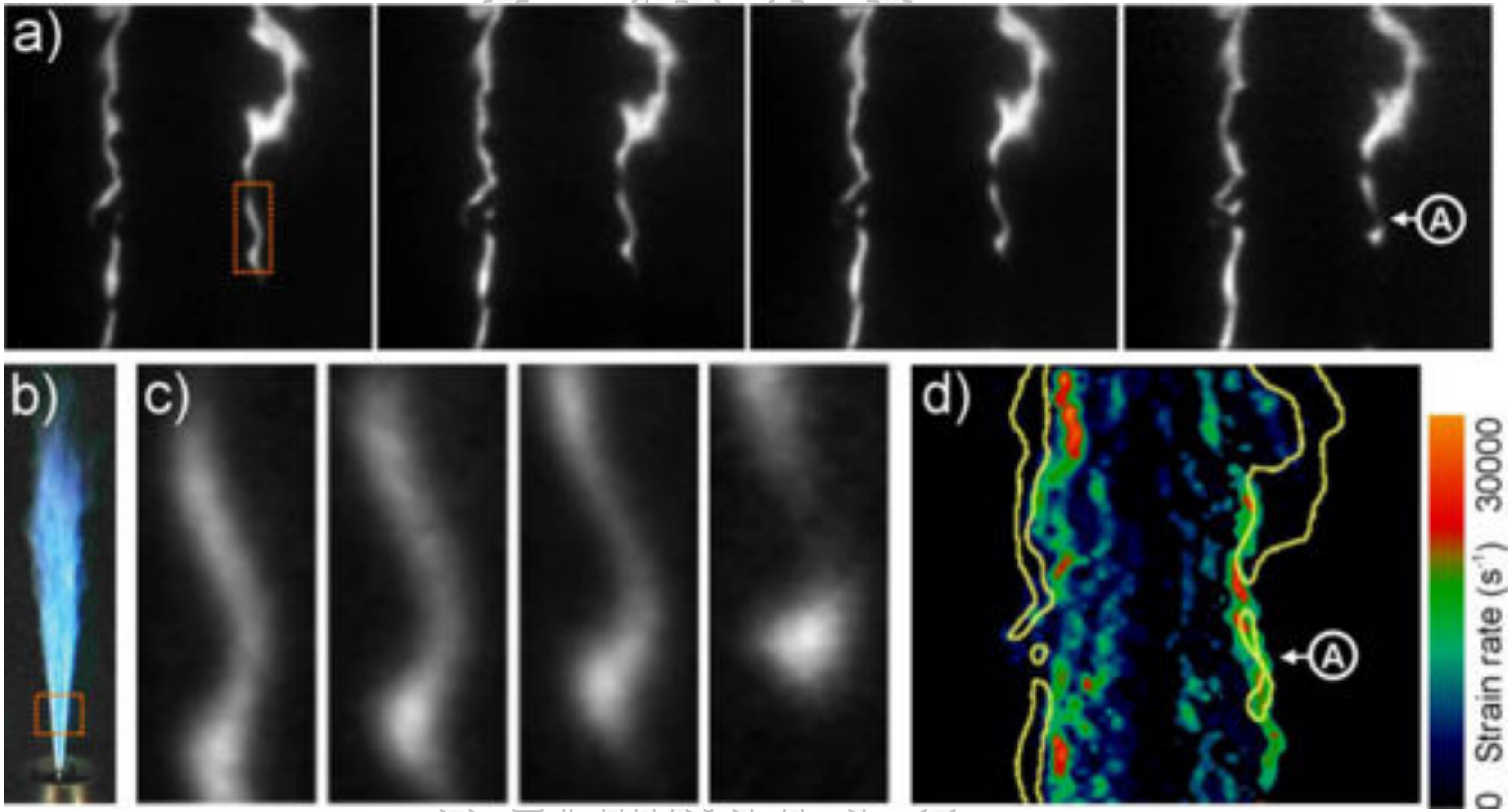


Local extinction of jet diffusion flames



Local extinction of jet diffusion flames



Flamelet equation

$$-\frac{1}{2}\rho\chi\frac{d^2Y_i}{dZ^2} = \omega_i$$

$$\frac{d^2Y_i}{dZ^2} = -\frac{2\omega_i}{\rho\chi}$$

$$\chi = 2\alpha(\nabla Z \cdot \nabla Z)$$

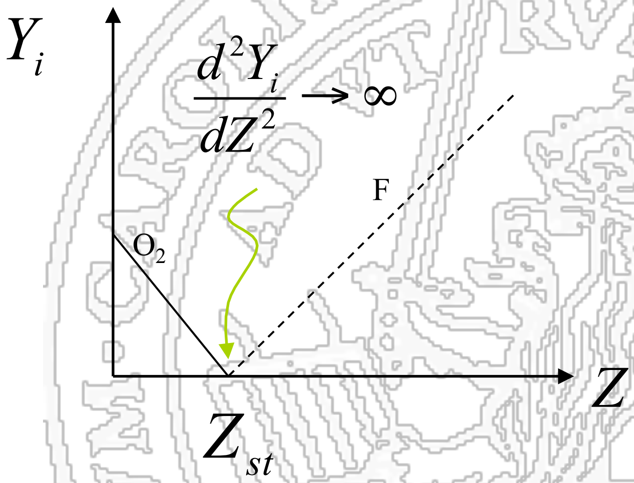
Scalar dissipation rate: mixing rate

Damköhler number Da = (mixing time)/(chemical reaction time)

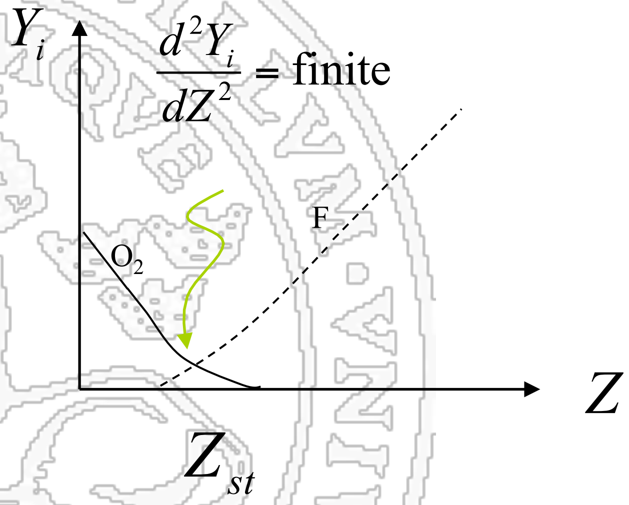
$$Da \sim \frac{2\omega_i}{\rho\chi}$$

Z_{st}

Finite rate chemistry effect



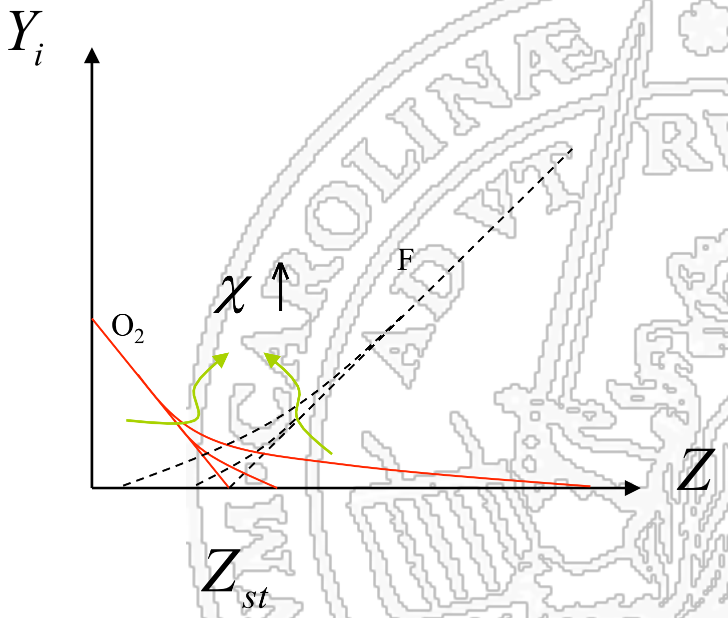
Damköhler number infinity

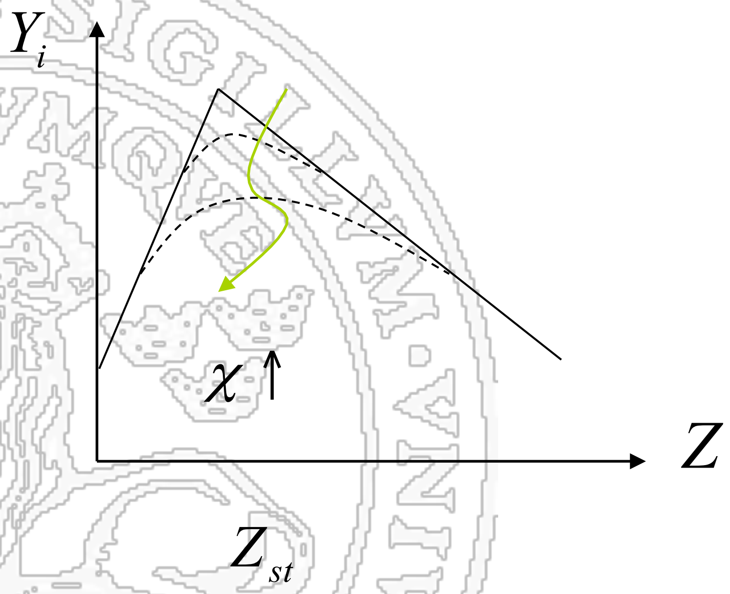


Damköhler not very high

$\chi \uparrow$

Effect of mixing rate

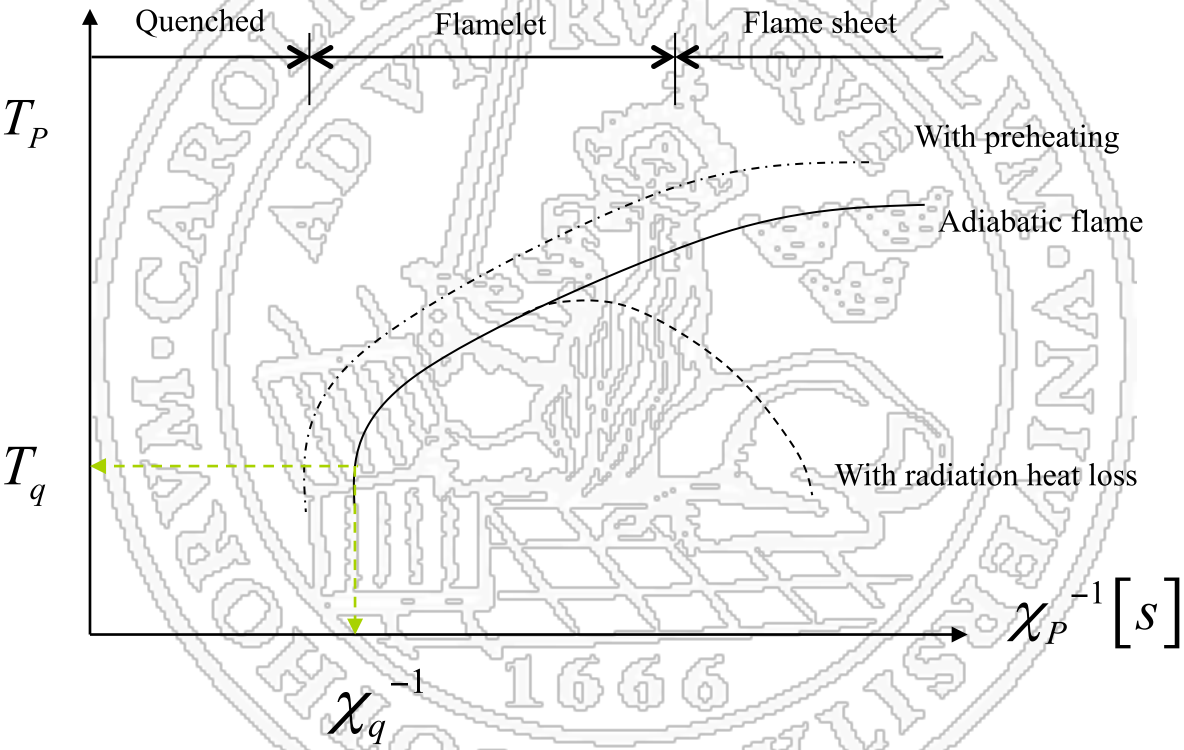




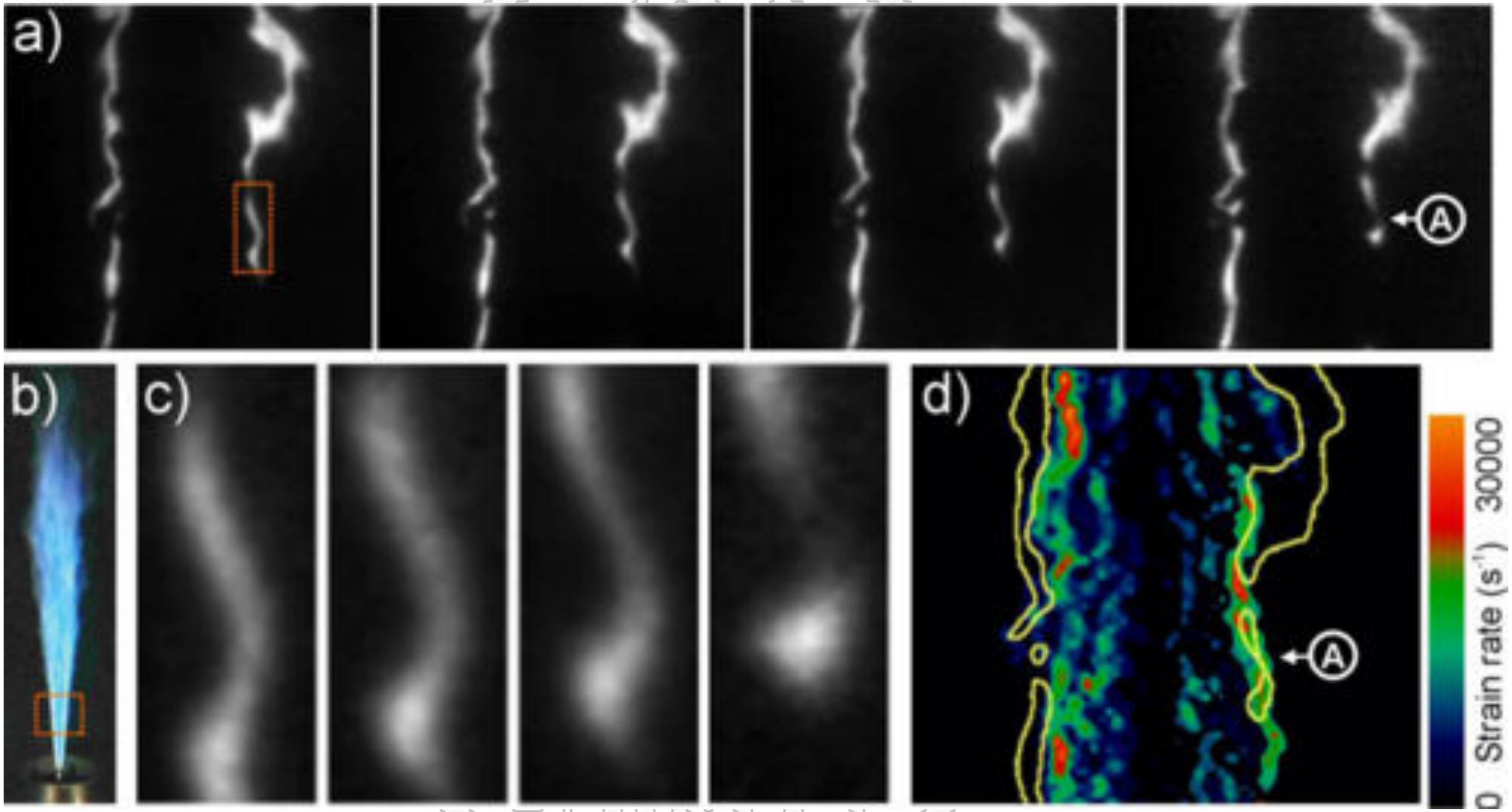
Increase of scalar dissipation rate leads to

- the leakage of fuel to the oxygen rich side increases
- the leakage of oxygen to the fuel rich side increases
- the flame temperature decreases, as a result of insufficient oxidation of the fuel

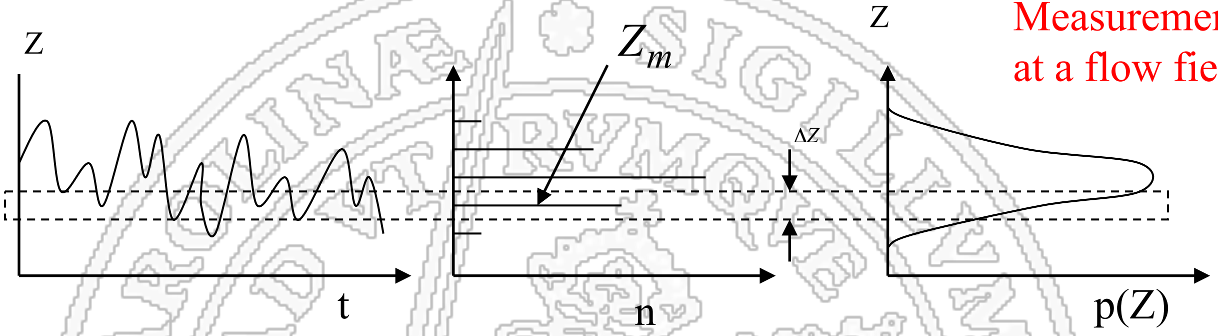
Flame quenching at high scalar dissipation rate



Local extinction of jet diffusion flames



Ensemble averaged mean flame – Burke-Schumann model



Measurement
at a flow field point

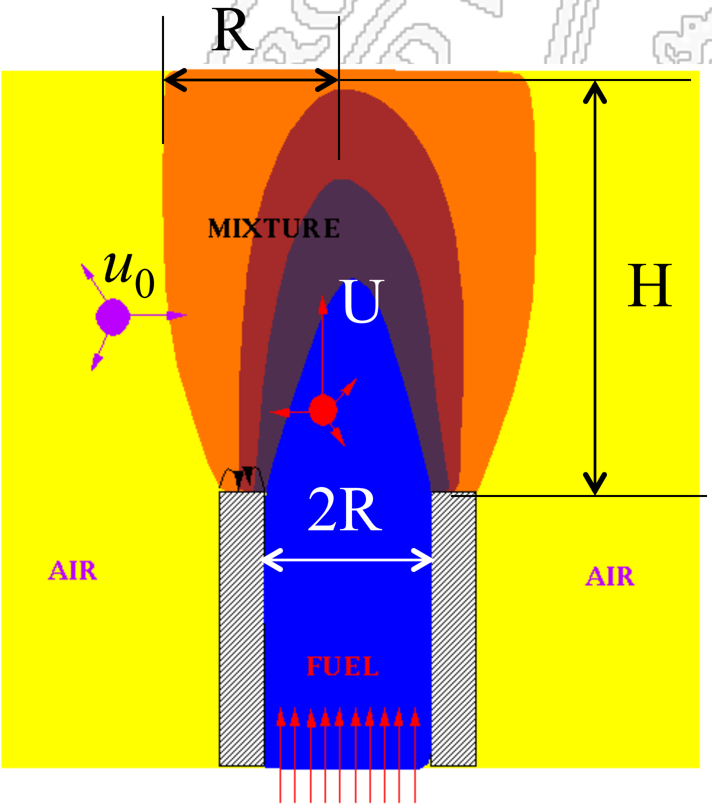
$$\overline{Y} = \frac{1}{N}\sum_{i=1}^{N} Y(Z(t_i)) \equiv \frac{1}{N}\sum_{m=1}^{M} n(Z_m)Y(Z_m) \equiv \sum_{m=1}^{M}\frac{n(Z_m)}{N\Delta Z}Y(Z_m)\Delta Z \equiv \int_0^1 p(Z)Y(Z)dZ$$

$$\overline{T} = \frac{1}{N}\sum_{i=1}^{N} T(Z(t_i)) \equiv \frac{1}{N}\sum_{m=1}^{M} n(Z_m)T(Z_m) \equiv \sum_{m=1}^{M}\frac{n(Z_m)}{N\Delta Z}T(Z_m)\Delta Z \equiv \int_0^1 p(Z)T(Z)dZ$$

Flamelet regime: flame height

Turbulent flame shape and flame height (3)

order of estimation



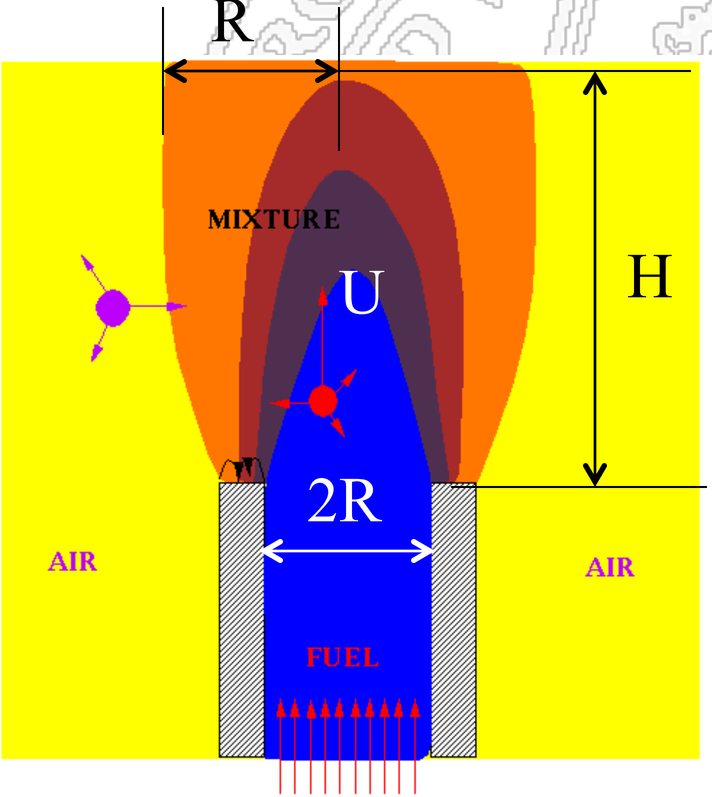
During time Δt, fuel molecule is convected from inlet to the tip of flame at a speed U, and oxygen molecule is transport by turbulence from air stream to the flame tip at a speed u_0.

$$\Delta t \propto \frac{H}{U} \propto \frac{R}{u_0}$$

$$\Rightarrow H \propto \frac{RU}{u_0} \propto \frac{R}{I}$$

$I=u_0/U$: intensity of turbulence

Recall: Laminar flame shape and flame height - *order of estimation*

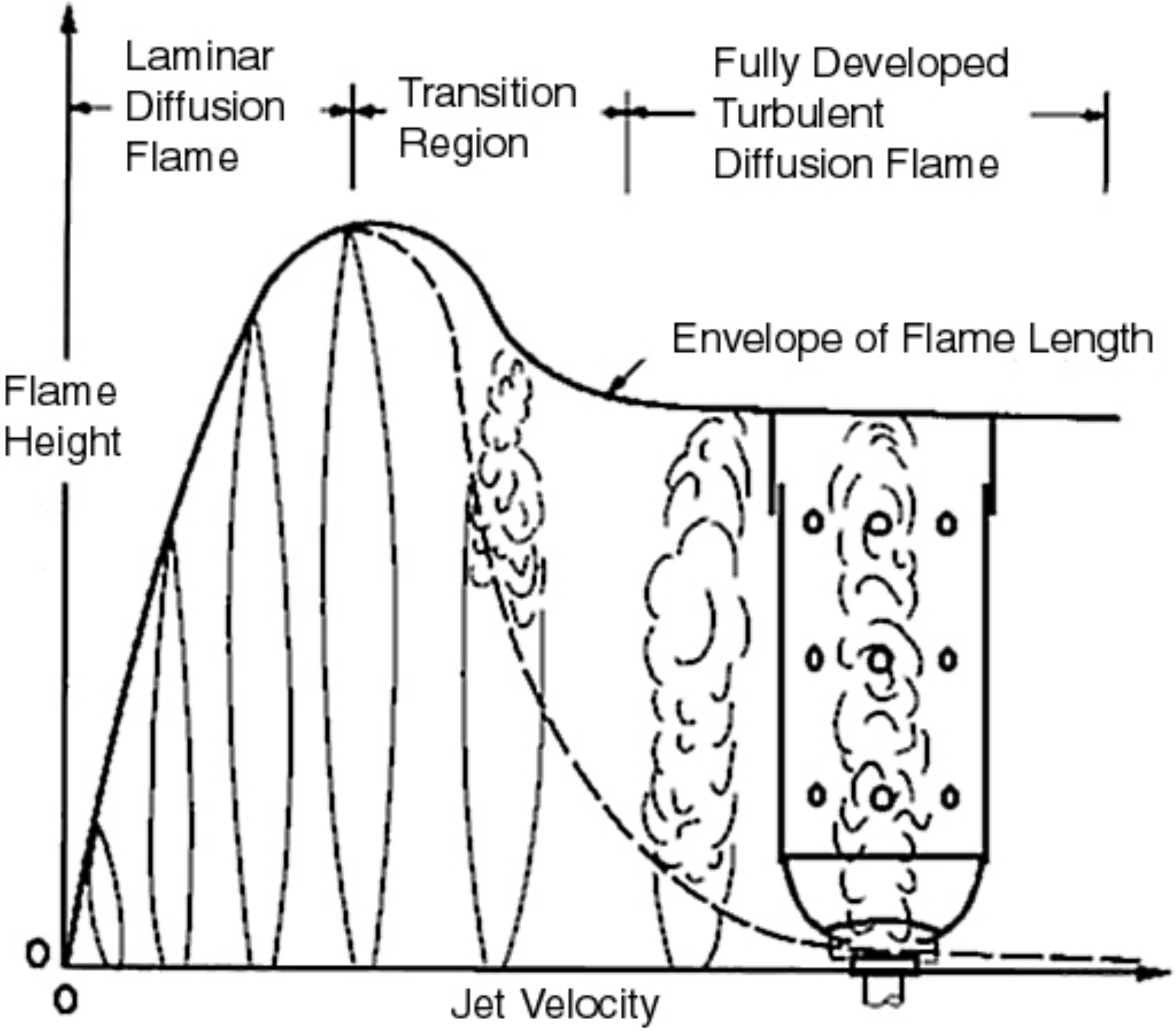


During time Δt, fuel molecule is convected from inlet to the tip of flame at a speed U, and oxygen molecule is diffused from air stream to the flame tip. D is diffusion coef.

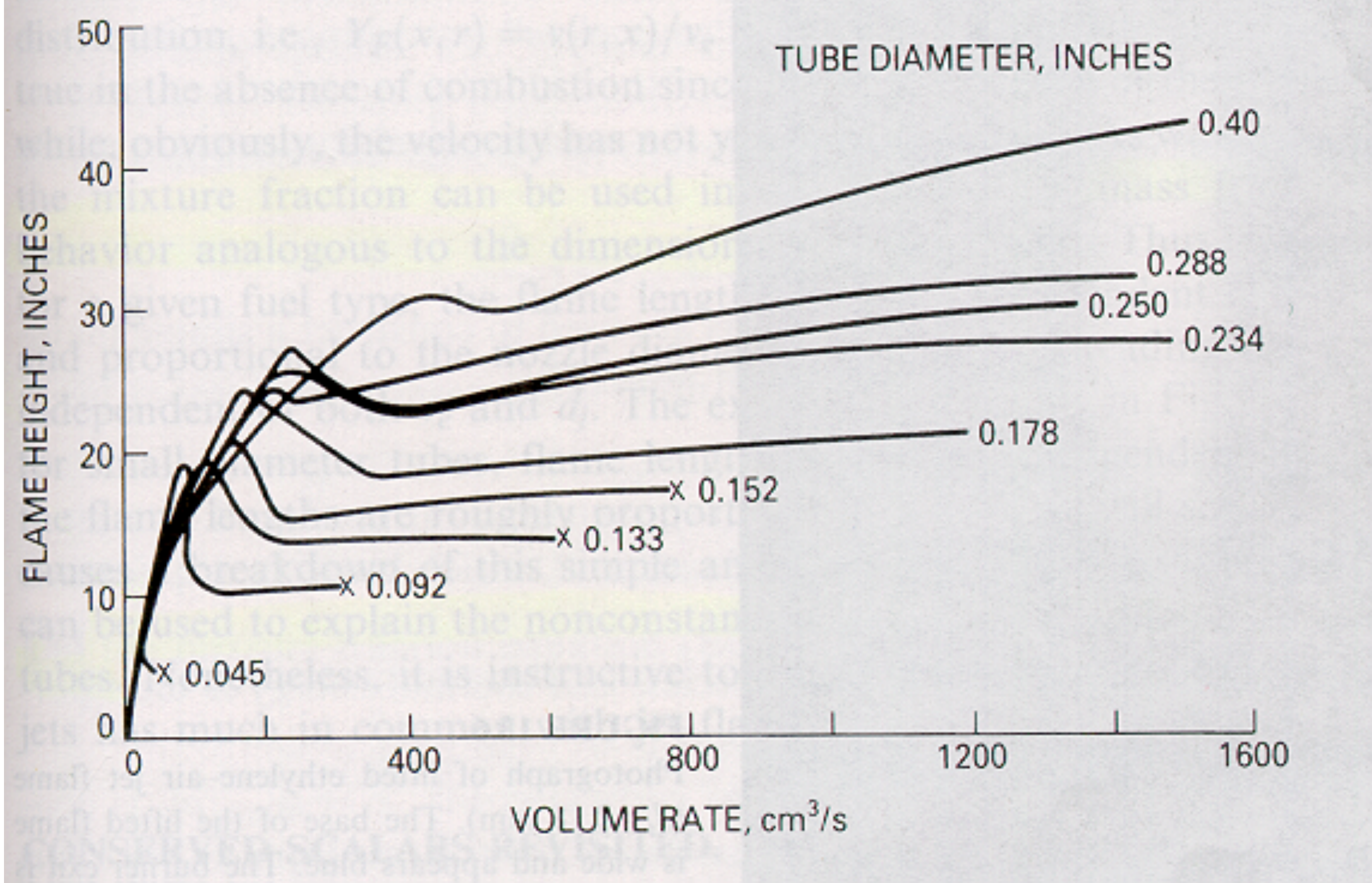
$$\Delta t \propto \frac{H}{U} \propto \frac{R^2}{D}$$

$$\Rightarrow H \propto \frac{R^2 U}{D}$$

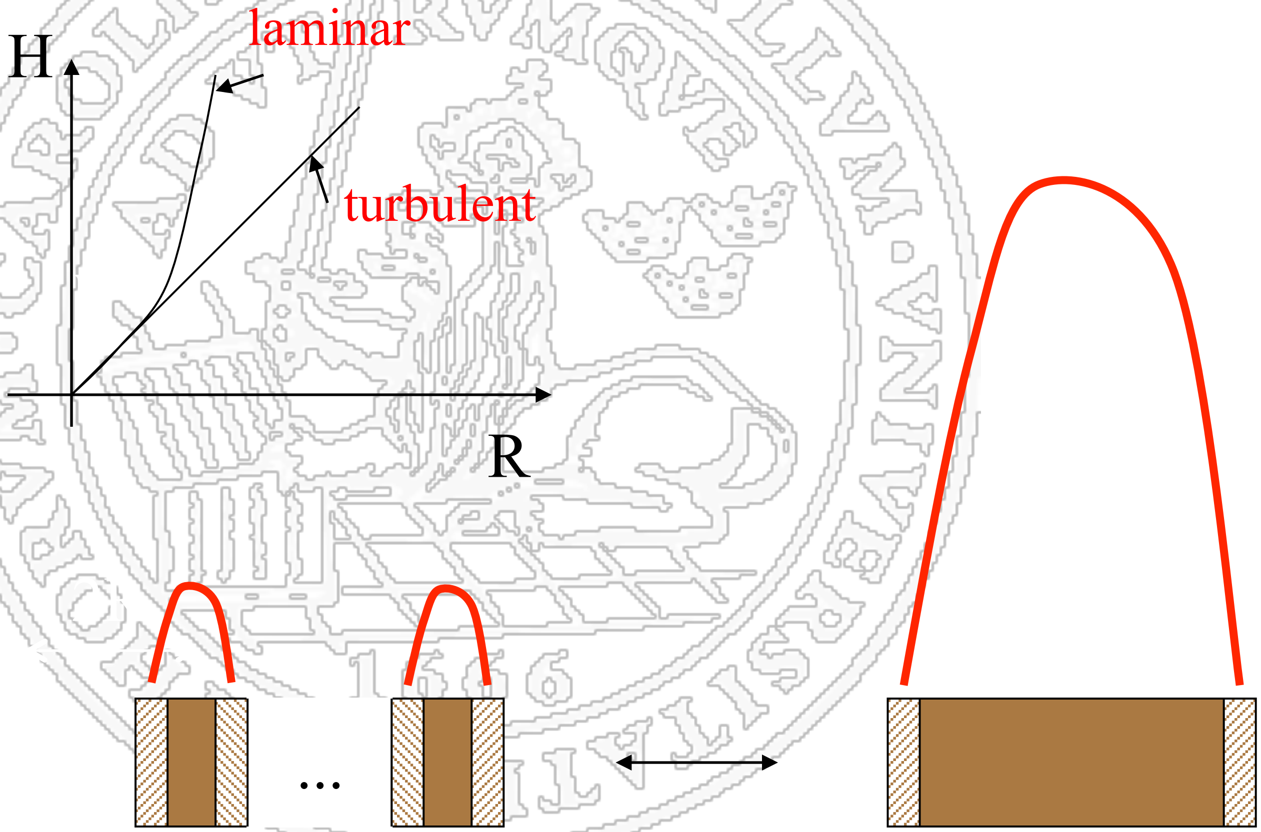
Dependence of flame height on injection speed



Dependence of flame height on injection speed



Dependence of flame height on burner diameter



Summary

- TNF structures
  - Three-zone structure: mixing – reaction – mixing
  - Reaction zone is highly wrinkled
  - Reaction zone is rather thin in physical space
  - Mixing is governed by turbulence eddy motion

- Turbulence flame interaction: laminar flamelet regime
  - Large eddies transport the fuel and air to the flame (slow)
  - Large eddies determine the overall mixing rate
  - Large eddies determine the flame height
  - Small eddies are responsible for the mixing on molecular scale
  - Small eddies can quench the flame