Turbulent Premixed Combustion

CEFRC Combustion Summer School

2014

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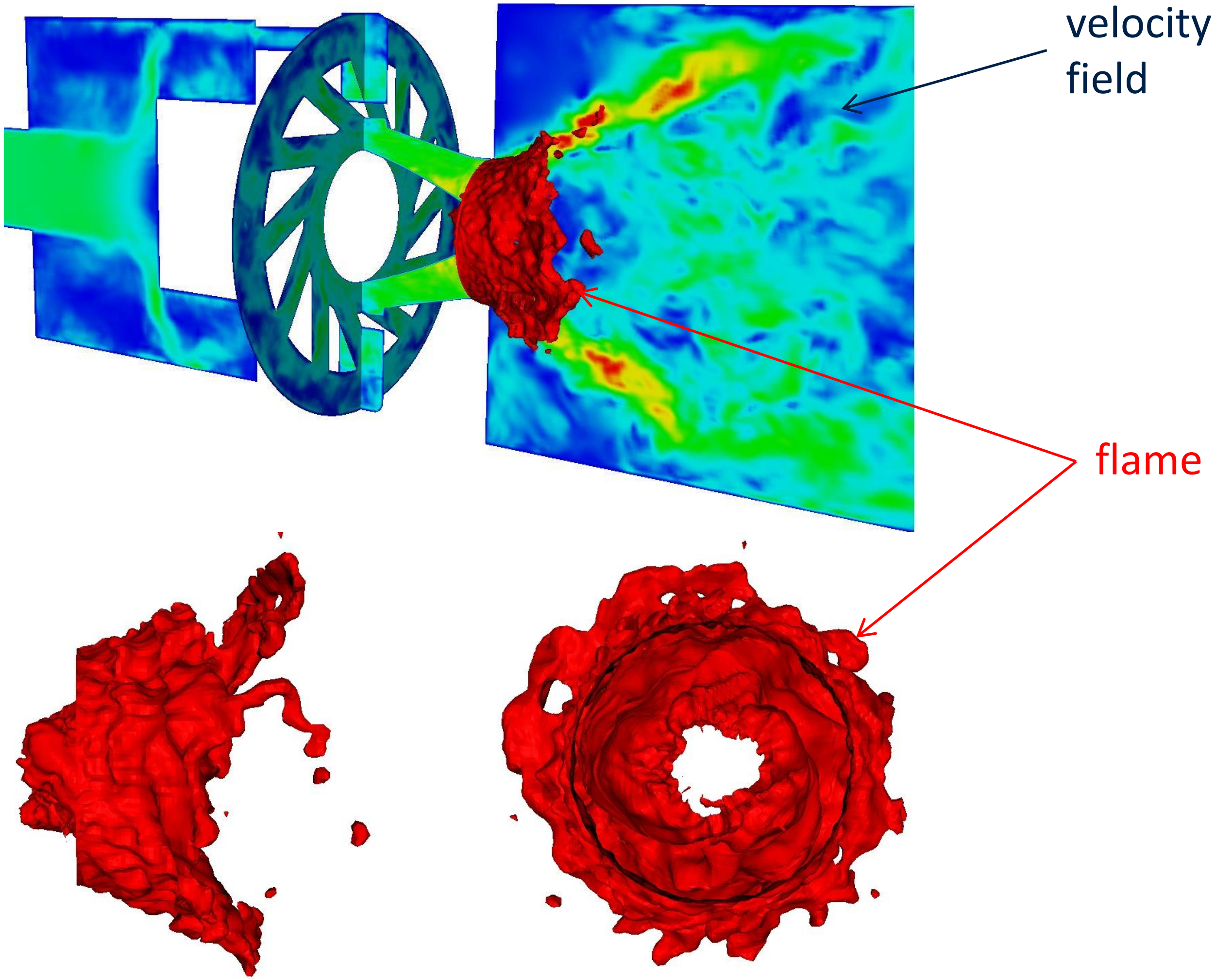
Example: LES of a stationary gas turbine



Course Overview

Part II: Turbulent Combustion

- Turbulence
- Turbulent Premixed Combustion
- Turbulent Non-Premixed Combustion
- Modelling Turbulent Combustion
- Applications

- Scales of Turbulent Premixed Combustion
- Regime-Diagram
- Turbulent Burning Velocity

Scales of Turbulent Premixed Combustion

- Integral turbulent scales

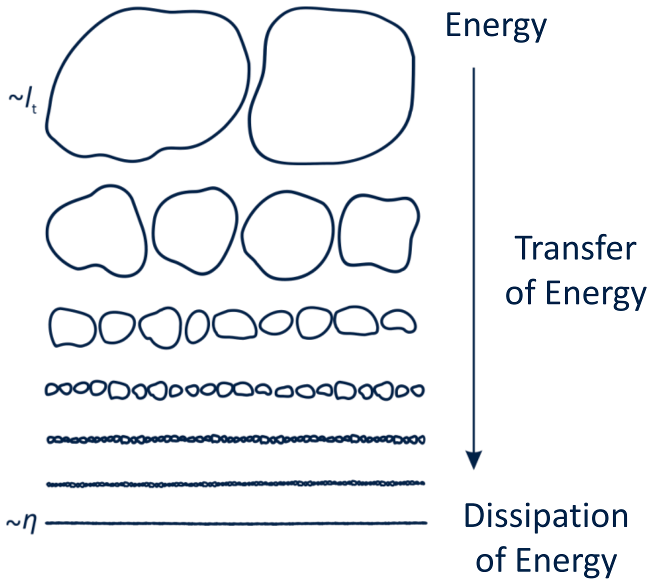
$$l_\mathrm{t} = c_1 \frac{\bar{k}^{3/2}}{\bar{\varepsilon}}, \qquad u' = \sqrt{\frac{2}{3}\bar{k}}, \qquad \tau = \frac{l_\mathrm{t}}{u'} \sim \frac{\bar{k}}{\bar{\varepsilon}}$$

- Smallest turbulent scales/Kolmogorov scales

$$\eta = \left(\frac{\nu^3}{\bar{\varepsilon}}\right)^{1/4}, \qquad u_\eta = (\nu\bar{\varepsilon})^{1/4}, \qquad t_\eta = \left(\frac{\nu}{\bar{\varepsilon}}\right)^{1/2}$$

- Flame thickness and time, reaction zone thickness

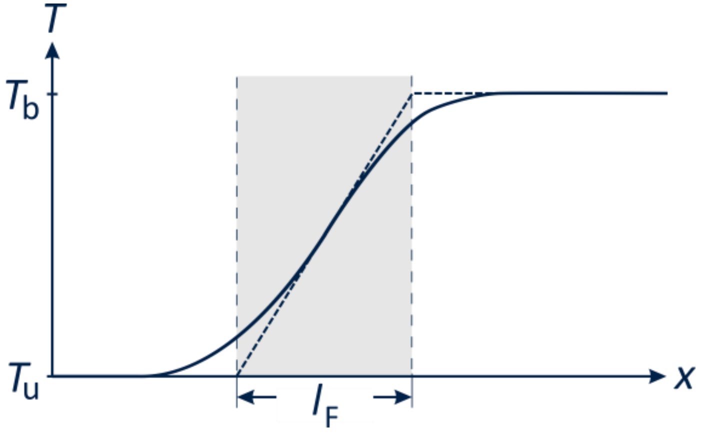
$$l_\mathrm{F} = \frac{D}{s_\mathrm{L}} = \frac{\lambda_\mathrm{b}}{\rho_\mathrm{u} c_p s_\mathrm{L}}, \qquad t_\mathrm{F} = \frac{l_\mathrm{F}}{s_\mathrm{L}} = \frac{D}{s_\mathrm{L}^2}, \qquad l_\delta \ll l_\mathrm{F}$$



Energy

Transfer of Energy

Dissipation of Energy



Dimensionless Quantities in Premixed Turbulent Combustion

- Turbulent Reynolds number

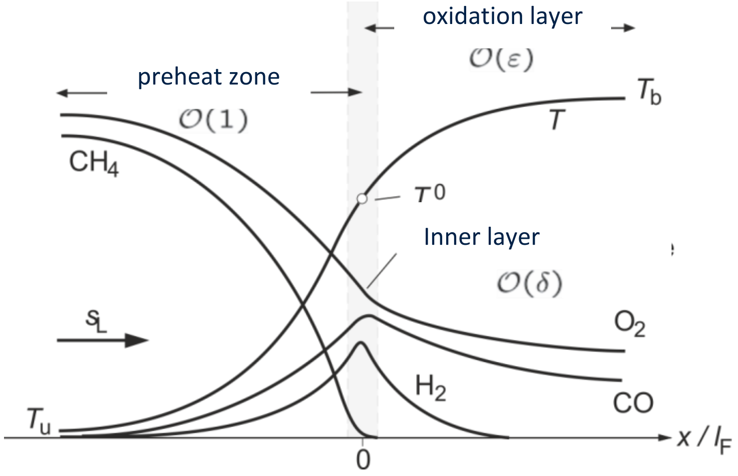
$$Sc = \frac{\nu}{D} = 1 \quad \rightarrow \quad Re_\mathrm{t} = \frac{l_\mathrm{t}}{l_\mathrm{F}}\,\frac{u'}{s_\mathrm{L}}$$

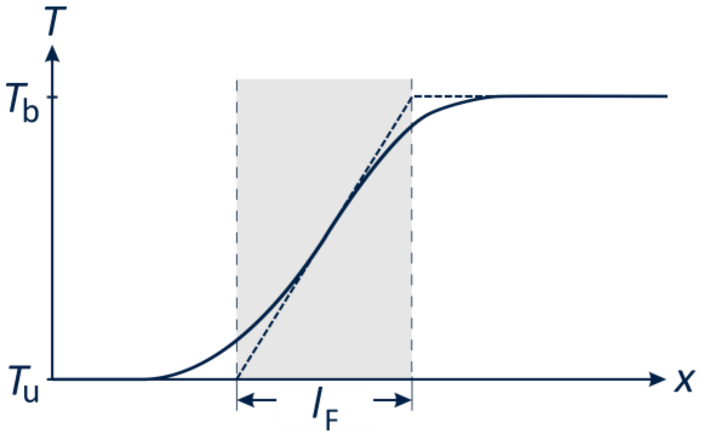
- Turbulent Damköhler number

$$Da_\mathrm{t} = \frac{\tau}{t_\mathrm{F}} = \frac{l_\mathrm{t}}{l_\mathrm{F}}\,\frac{s_\mathrm{L}}{u'}$$

- Karlovitz number (interaction of small-scale turbulence with the flame)

$$Ka = \frac{t_\mathrm{F}}{t_\eta} = \frac{l_\mathrm{F}^2}{\eta^2} = \sqrt{\frac{l_\mathrm{F}}{l_\mathrm{t}}\left(\frac{u'}{s_\mathrm{L}}\right)^3} \quad \text{und} \quad Ka_\delta = \frac{l_\delta^2}{\eta^2} = \overset{\overset{\delta \approx 0{,}1}{\searrow}}{\delta^2}\,Ka$$





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Regime Diagram

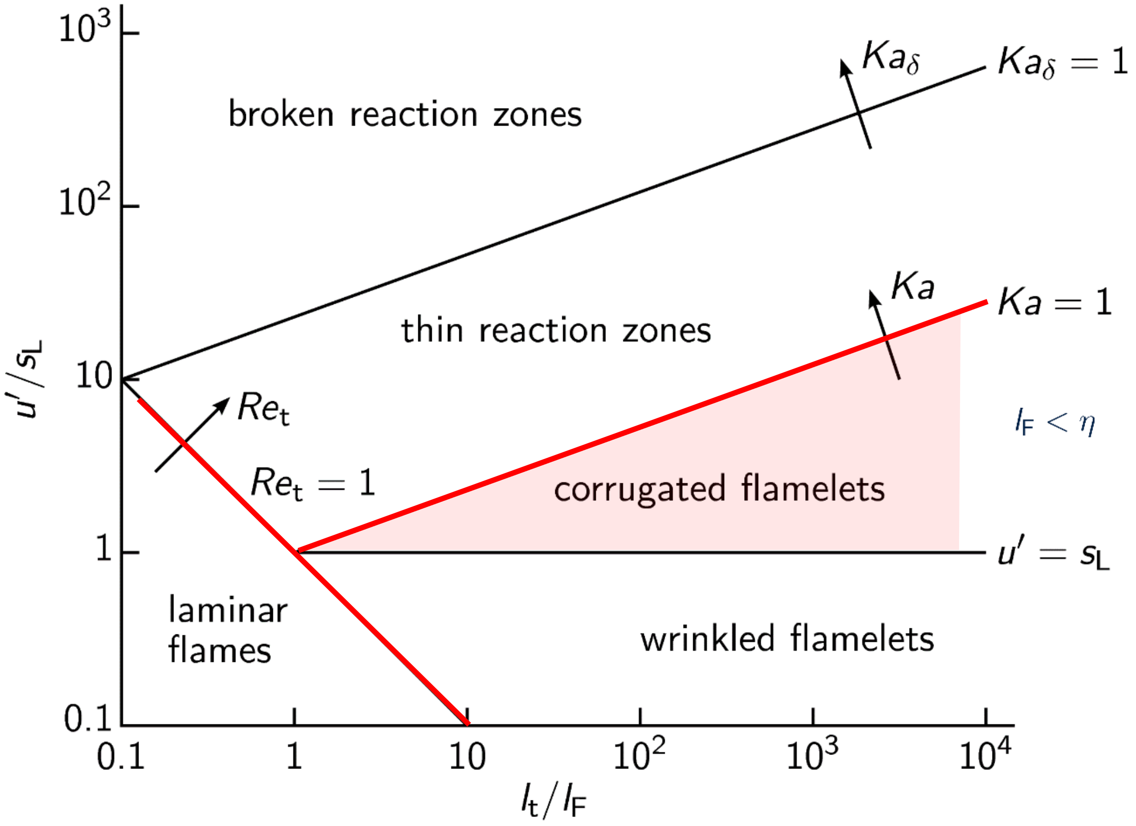
Corrugated Flamelet Regime

$$Re_t = \frac{l_t}{l_F}\frac{u'}{s_L}$$

$$Ka^2 = \left(\frac{l_t}{l_F}\right)^{-1}\left(\frac{u'}{s_L}\right)^3$$

$$Da_t = \frac{l_t}{l_F}\left(\frac{u'}{s_L}\right)^{-1}$$

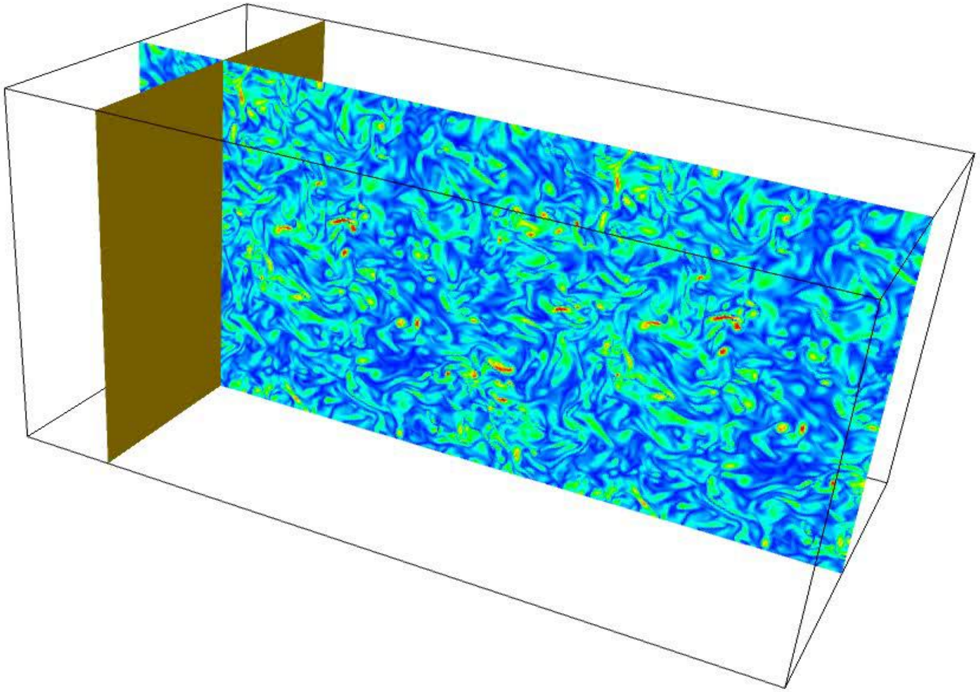
→



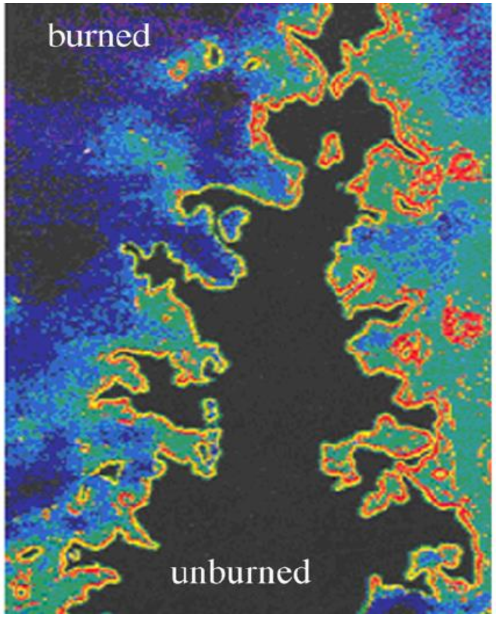
Regime Diagram: Corrugated Flamelets

- $Ka < 1 \rightarrow \eta > l_F$
  - Interaction of a very thin flame with a turbulent flow
  - Assumption: infinitely thin flame (compared to turbulent scales)

premixed flame in isotropic turbulence



OH-radical-distribution in a turbulent premixed flame



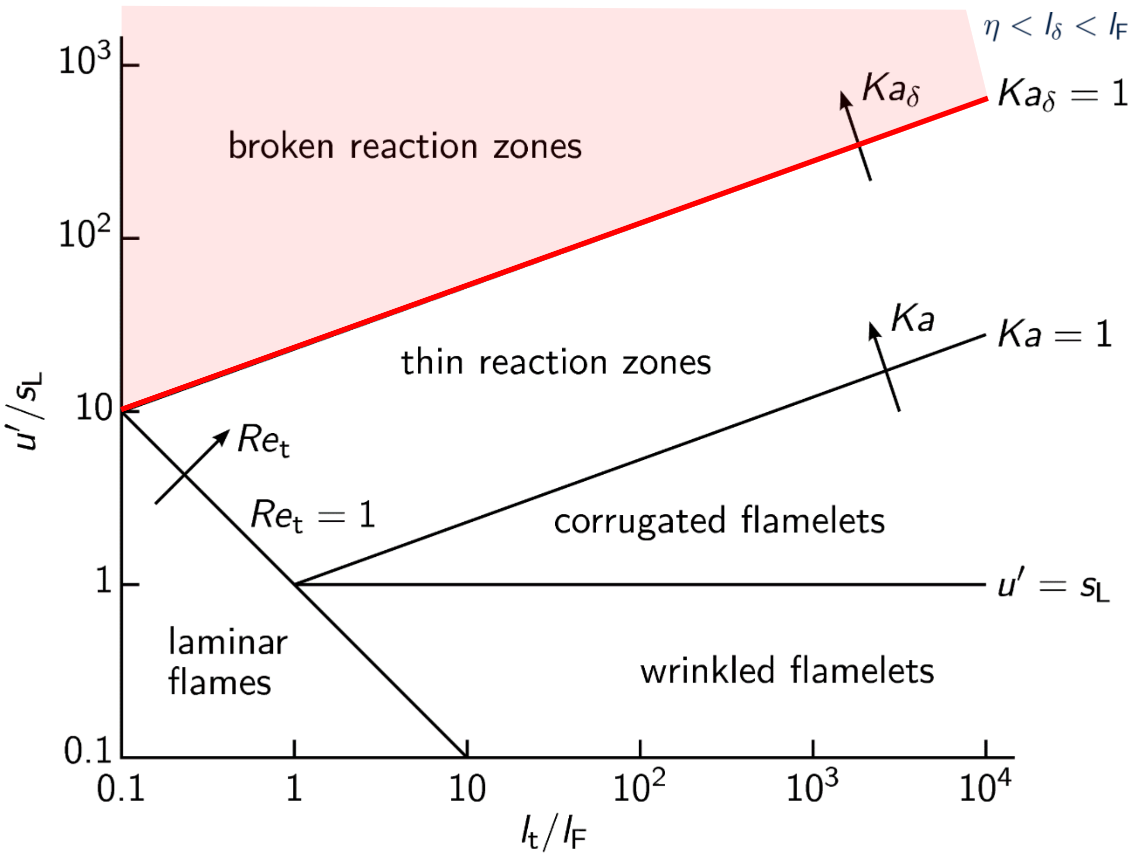
Buschmann (1996)

Regime Diagramm: Broken Reaction Zones Regime

$$Re_t = \frac{l_t}{l_F}\frac{u'}{s_L}$$

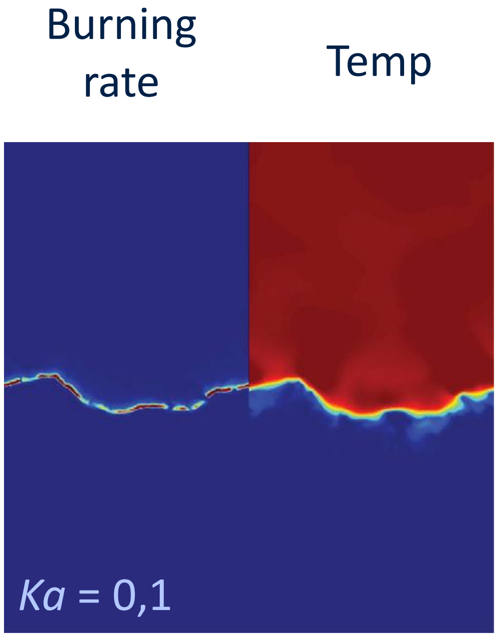
$$Ka^2 = \left(\frac{l_t}{l_F}\right)^{-1}\left(\frac{u'}{s_L}\right)^{3}$$

$$Da_t = \frac{l_t}{l_F}\left(\frac{u'}{s_L}\right)^{-1}$$

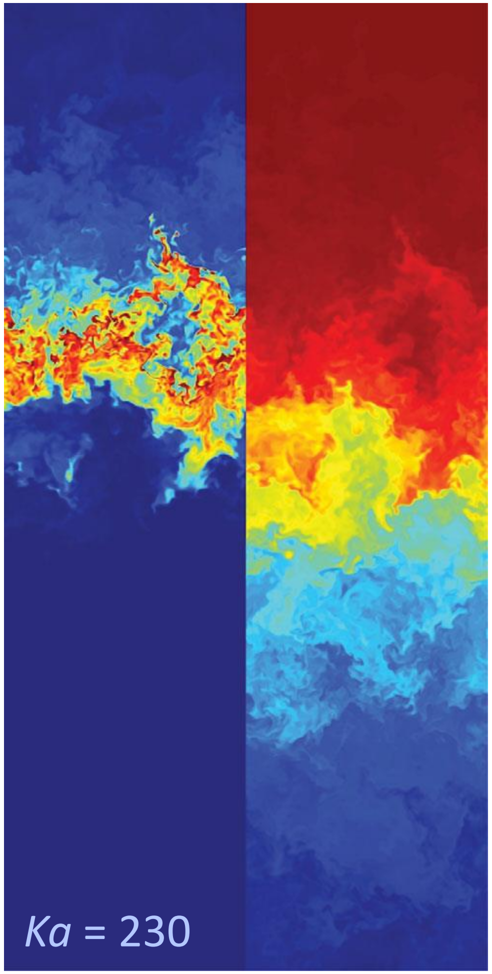


Regime Diagramm: Broken Reaction Zones Regime

- $Ka_\delta > 1 \rightarrow \eta < l_\delta$
  - Smallest turbulent eddies enter the reaction zones
  - Turbulent transport → radicals are removed from reaction zone
  - Local extinguishing in the inner reaction zone
    - Overall extinguishing of the flame front is possible



Two-dimensional slices from three-dimensional simulations of low- and high-Karlovitz-supernovae flames, respectively. The left-hand panel in each case is burning rate, and the right-hand panel is temperature.



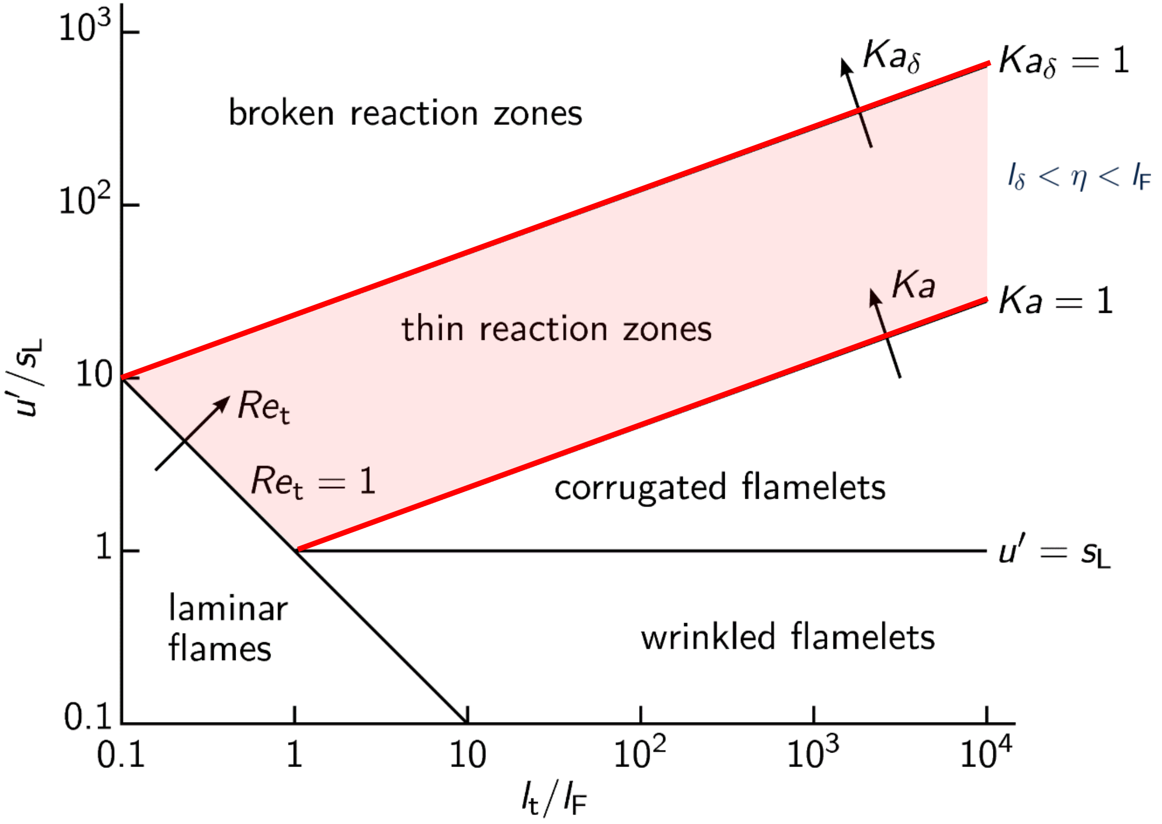
Source: A. J. Aspden et al. (JFM 2011)

Regime Diagramm: Thin Reaction Zones Regime

$$Re_t = \frac{l_t}{l_F}\frac{u'}{s_L}$$

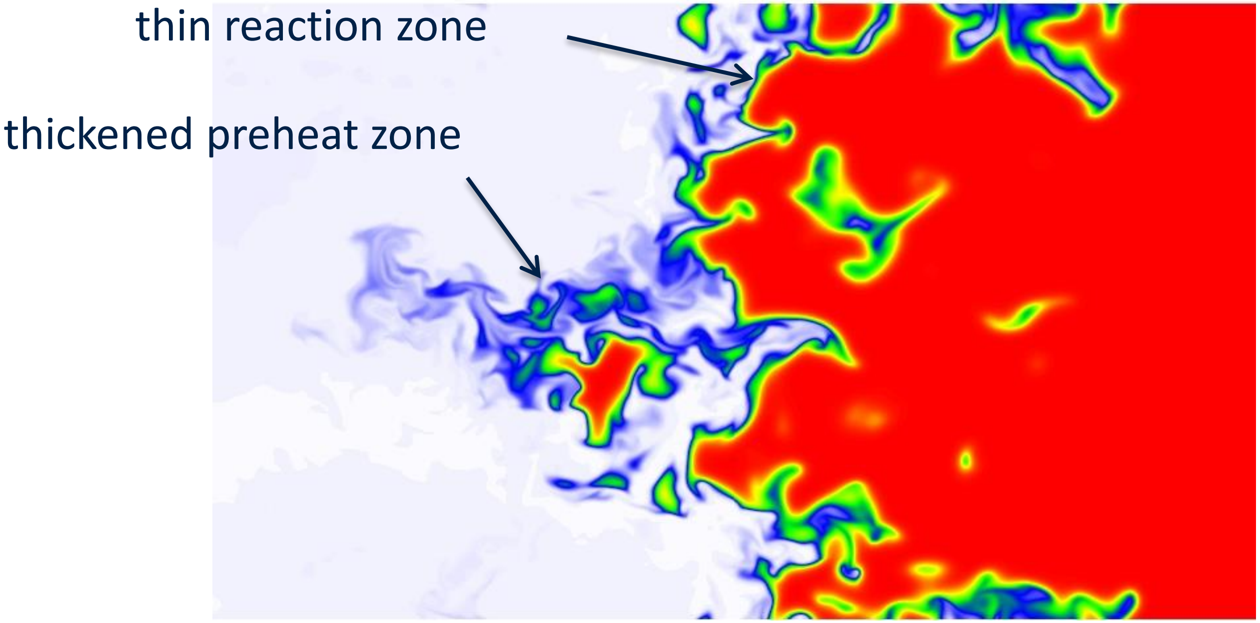
$$Ka^2 = \left(\frac{l_t}{l_F}\right)^{-1}\left(\frac{u'}{s_L}\right)^3$$

$$Da_t = \frac{l_t}{l_F}\left(\frac{u'}{s_L}\right)^{-1}$$



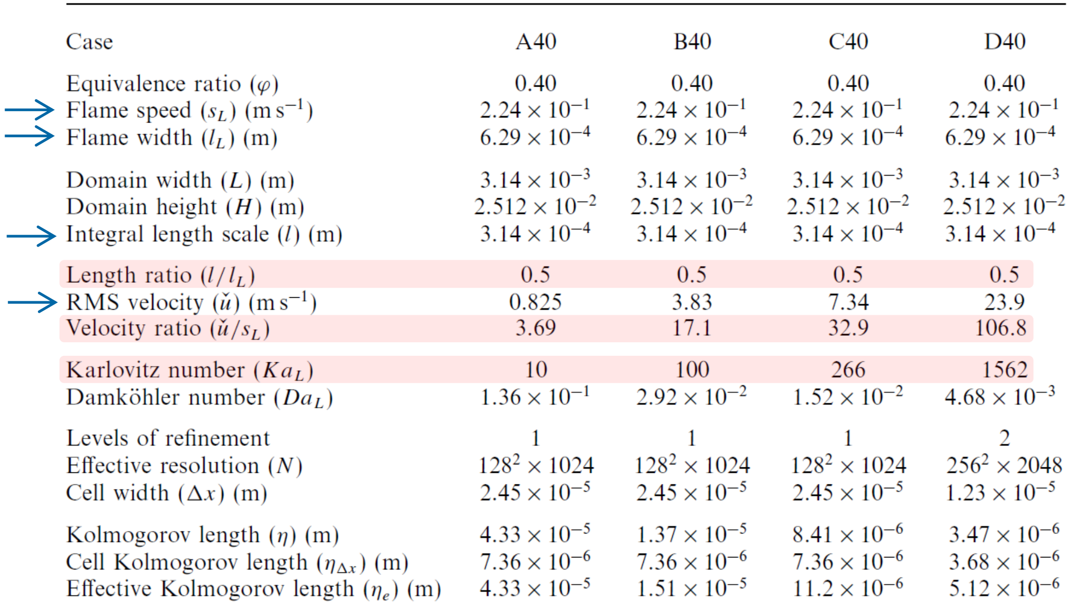
Regime Diagramm: Thin Reaction Zones Regime

- $Ka > 1$ und $Ka_\delta < 1 \rightarrow l_\delta < \eta < l_F$
  - With $l_\delta \approx 0{,}1 l_F \rightarrow Ka \approx 100 Ka_\delta$
  - Turbulent mixing inside preheat zone
  - Assumption: infinitely thin reaction zone (compared to turbulent scales)



temperature distribution from DNS of a premixed turbulent flame

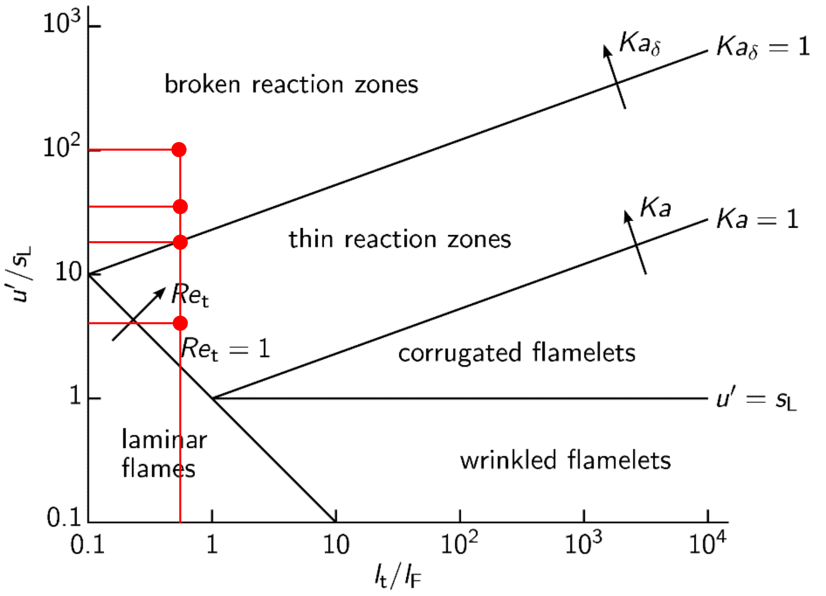
Regime Diagram: Résumé



Case	A40	B40	C40	D40
Equivalence ratio (φ)	0.40	0.40	0.40	0.40
Flame speed (s_L) ($\mathrm{m\,s^{-1}}$)	2.24×10^{-1}	2.24×10^{-1}	2.24×10^{-1}	2.24×10^{-1}
Flame width (l_L) (m)	6.29×10^{-4}	6.29×10^{-4}	6.29×10^{-4}	6.29×10^{-4}
Domain width (L) (m)	3.14×10^{-3}	3.14×10^{-3}	3.14×10^{-3}	3.14×10^{-3}
Domain height (H) (m)	2.512×10^{-2}	2.512×10^{-2}	2.512×10^{-2}	2.512×10^{-2}
Integral length scale (l) (m)	3.14×10^{-4}	3.14×10^{-4}	3.14×10^{-4}	3.14×10^{-4}
Length ratio (l/l_L)	0.5	0.5	0.5	0.5
RMS velocity ($\check{u}$) ($\mathrm{m\,s^{-1}}$)	0.825	3.83	7.34	23.9
Velocity ratio ($\check{u}/s_L$)	3.69	17.1	32.9	106.8
Karlovitz number (Ka_L)	10	100	266	1562
Damköhler number (Da_L)	1.36×10^{-1}	2.92×10^{-2}	1.52×10^{-2}	4.68×10^{-3}
Levels of refinement	1	1	1	2
Effective resolution (N)	$128^2 \times 1024$	$128^2 \times 1024$	$128^2 \times 1024$	$256^2 \times 2048$
Cell width (Δx) (m)	2.45×10^{-5}	2.45×10^{-5}	2.45×10^{-5}	1.23×10^{-5}
Kolmogorov length (η) (m)	4.33×10^{-5}	1.37×10^{-5}	8.41×10^{-6}	3.47×10^{-6}
Cell Kolmogorov length ($\eta_{\Delta x}$) (m)	7.36×10^{-6}	7.36×10^{-6}	7.36×10^{-6}	3.68×10^{-6}
Effective Kolmogorov length (η_e) (m)	4.33×10^{-5}	1.51×10^{-5}	11.2×10^{-6}	5.12×10^{-6}

TABLE 2. Turbulent flame properties for the four simulations at equivalence ratio $\varphi = 0.40$.

Source: A. J. Aspden et al. (JFM 2011)



Regime Diagram: Résumé

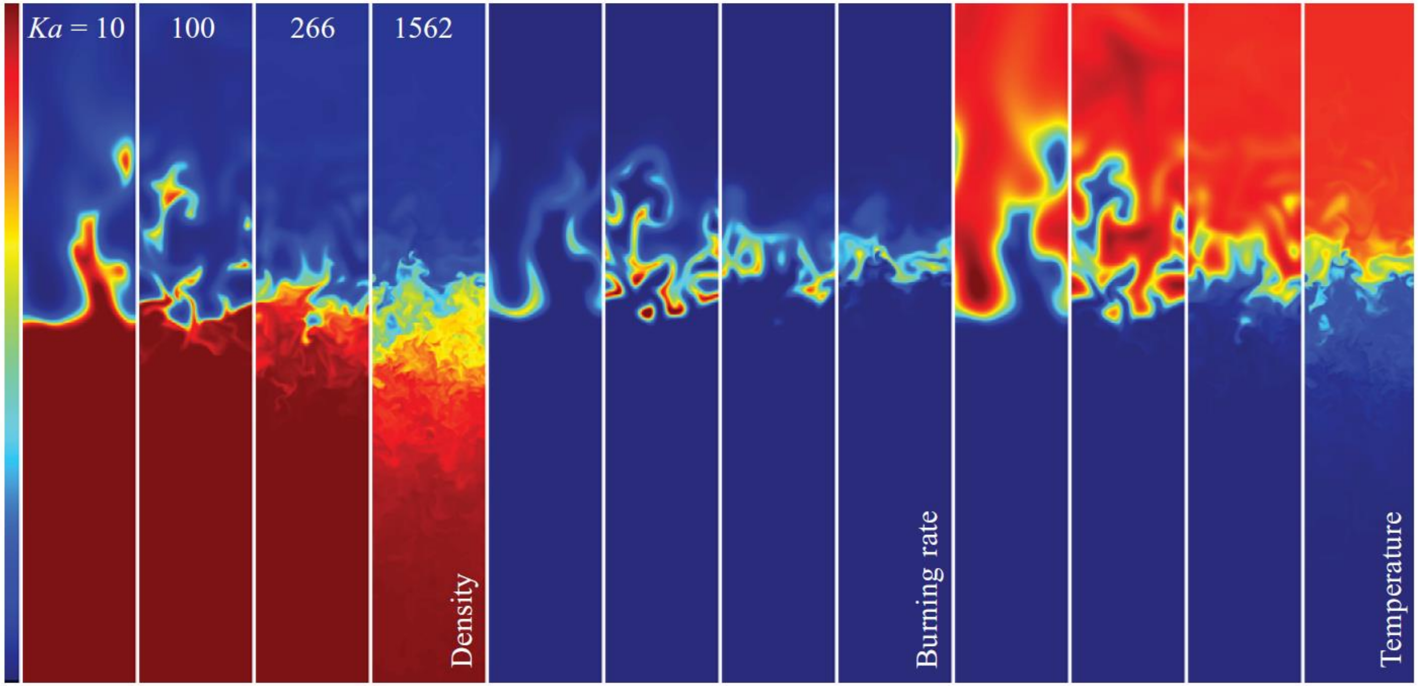


FIGURE 8. Two-dimensional vertical slices through three-dimensional simulations showing density, burning rate and temperature at $\varphi = 0.40$, respectively. The density, burning rate and temperature ranges are [0.2,1.02] kg m^{-3}, [0,64] kg m^{-3} s^{-1} and [298,1600] K, respectively.

Source: A. J. Aspden et al. (JFM 2011)

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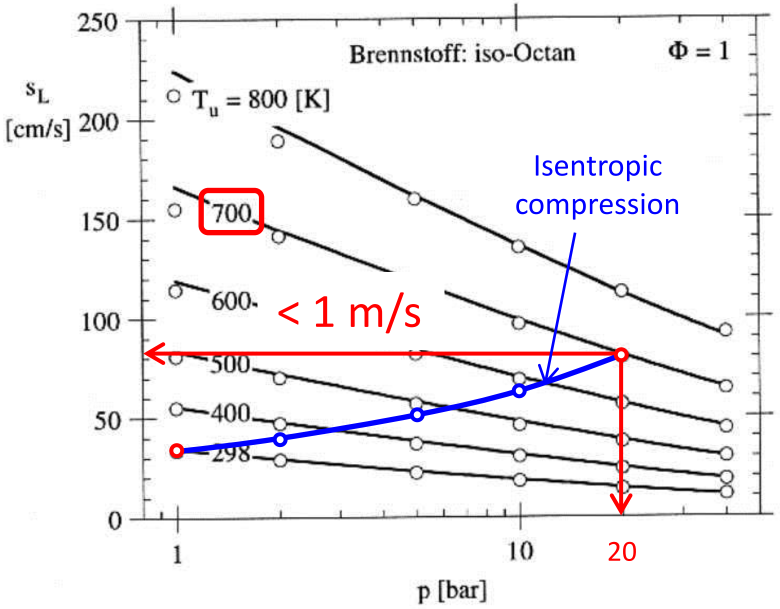
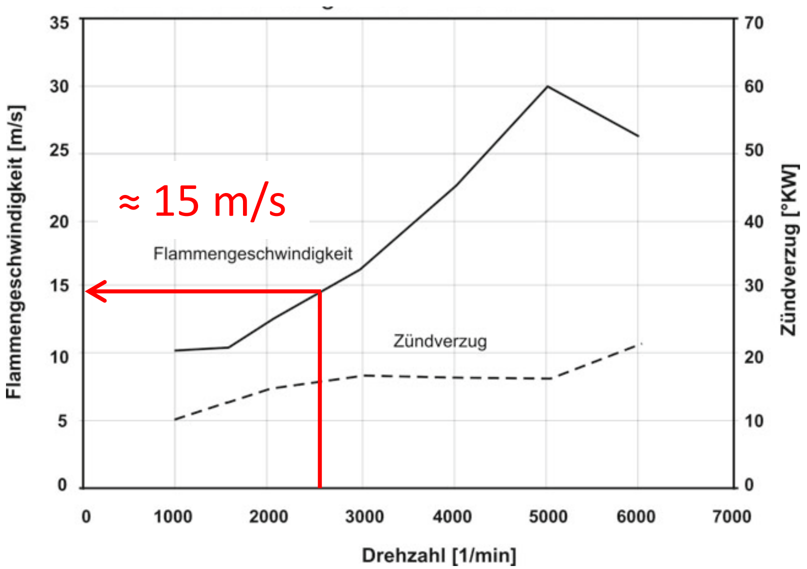
Turbulent Burning Velocity

Comparison: Laminar/Measured Burning Velocity

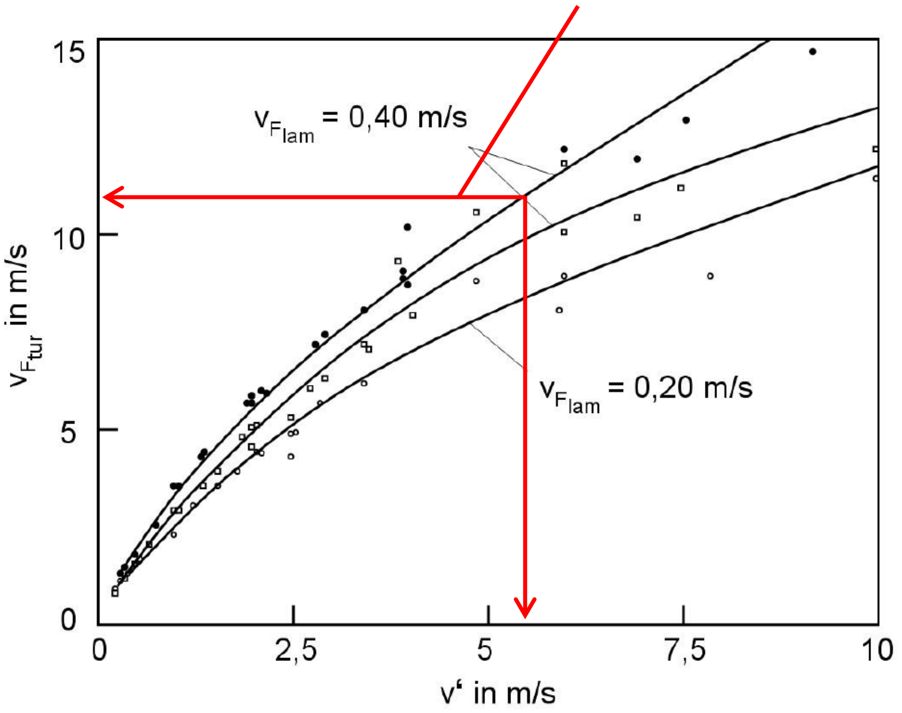


Laminar burning velocity
of iso-octane



Exemplary measurements in gasoline engine with tumble generator of flame velocity at spark plug position during full load (Source: Merker, „Grundlagen Verbrennungsmotoren“)

Comparison: Laminar/Measured Burning Velocity

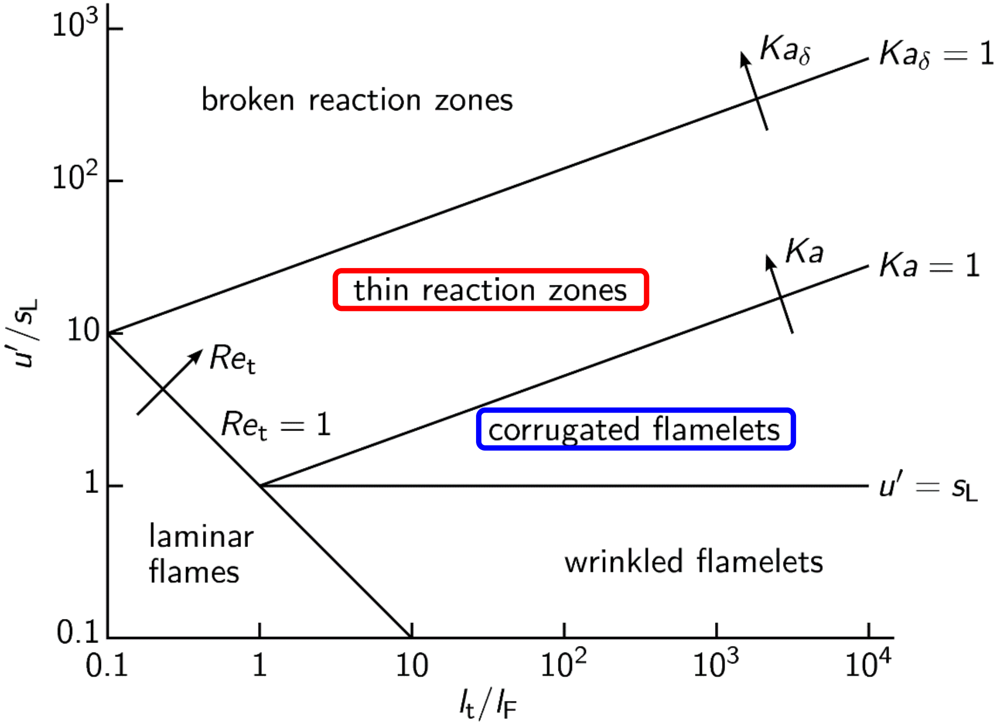


≈factor 30

Experimental data of s_T vs. wrinkled laminar-flame theories of turbulent flame propagation
(data from Turns 2000)

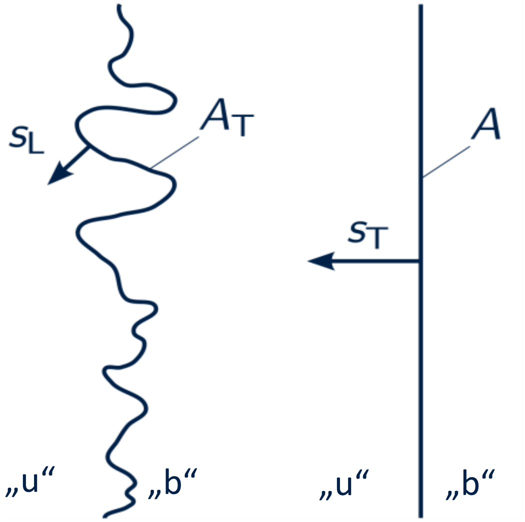
Turbulent Burning Velocity

- Main problem for turbulent premixed combustion:
  Quantification of turbulent burning velocity s_T
- s_T: Velocity which quantifies the propagation of the turbulent flame front into unburnt mixture
- Distinction of two limiting cases by Damköhler (1940)
  1. Large scale turbulence ↔ corrugated flamelets
  2. Small scale turbulence ↔ thin reaction zones



Turbulent Burning Velocity: Corrugated Flamelets

- Instantaneous flame front
  - Flame surface area A_T
  - Propagates locally with laminar burning velocity s_L into unburnt mixture
- Mean flame front
  - Mean flame surface area A
  - Propagates with turbulent burning velocity s_T



Turbulent Burning Velocity: Corrugated Flamelets

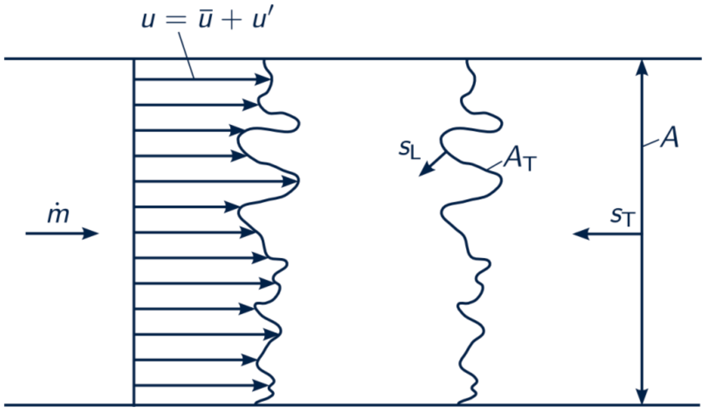
- With the mass flux trough A and A_T

$$\dot{m} = \rho_\mathrm{u} s_\mathrm{L} A_\mathrm{T} = \overline{\rho}_\mathrm{u} s_\mathrm{T} A$$

- Assume constant density in the unburnt mixture (assumption) $(\rho_\mathrm{u} = \overline{\rho}_\mathrm{u})$

$$\boxed{\frac{s_\mathrm{T}}{s_\mathrm{L}} = \frac{A_\mathrm{T}}{A}}$$

- Wrinkling of the laminar flame (A_T↑) → increase of s_T



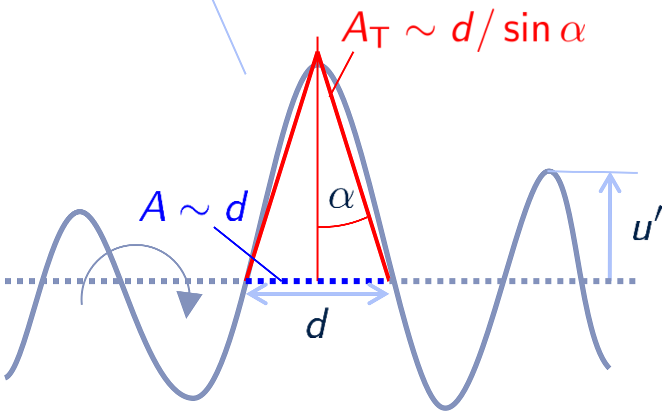
Turbulent Burning Velocity: Corrugated Flamelets

- Turbulence → flame surface area ↑
- Using an analogy with a Bunsen flame

$$s_\mathrm{L} = u_\mathrm{u} \sin\alpha \quad \xrightarrow{\text{hier}} \quad \sin\alpha = \frac{s_\mathrm{L}}{u'} \quad \Rightarrow \quad \frac{A_\mathrm{T}}{A} \sim \frac{d/\sin\alpha}{d} = \frac{u'}{s_\mathrm{L}}$$

- Limit for $u' \to 0$

$$\boxed{\frac{s_\mathrm{T}}{s_\mathrm{L}} = \frac{A_\mathrm{T}}{A} = 1 + \frac{u'}{s_\mathrm{L}}}$$



- Internal combustion engine:
  - Engine speed n↑ → burning velocity s_T↑ due to

$$u' \sim u_\mathrm{piston} \sim n$$

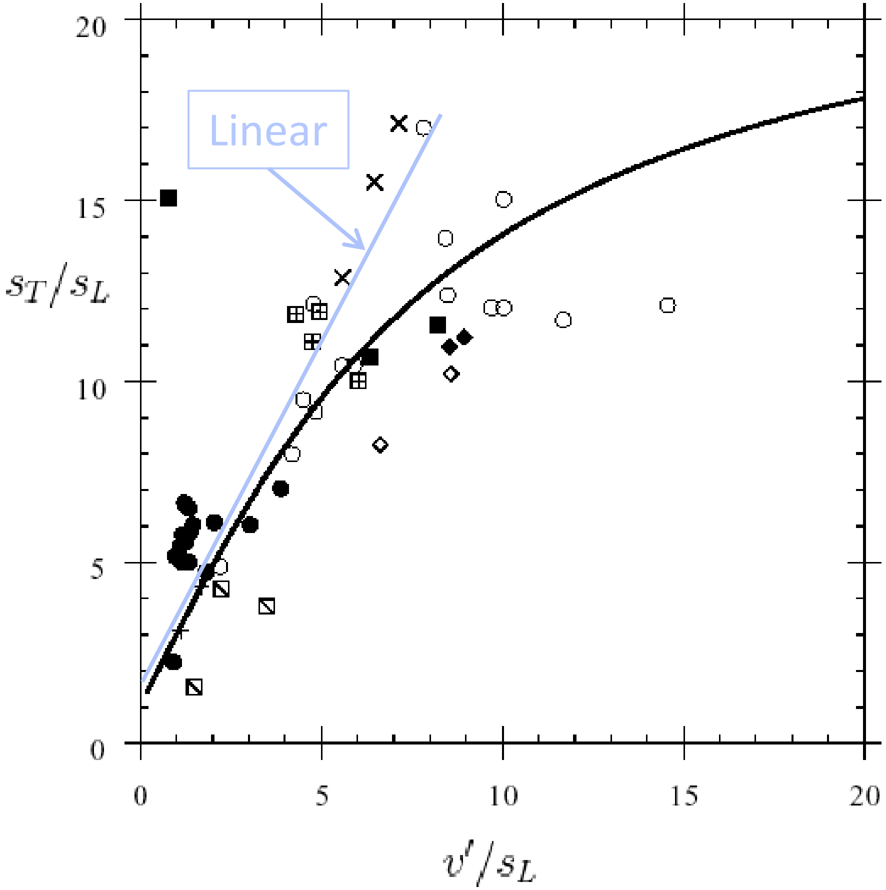
→ High engine speed achievable

Turbulent Burning Velocity: large-scale turbulence

- In experiments often used empirical relation

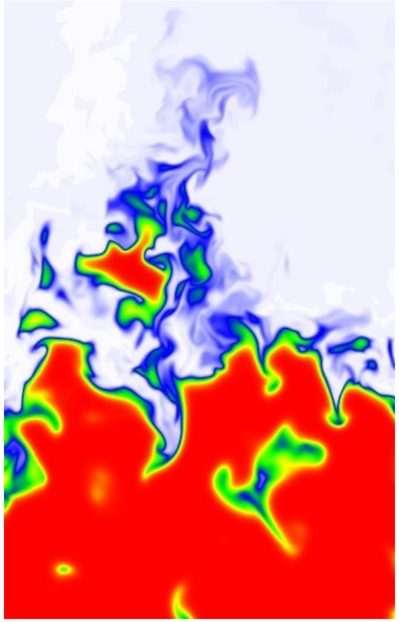
$$\frac{s_\mathrm{T}}{s_\mathrm{L}} = 1 + C\left(\frac{u'}{s_\mathrm{L}}\right)^n$$

  - Constant *C* experimentally determined
  - Typical values: $0.5 < n < 1.0$
- From experimental data →
  - For small *u*‘, $s_\mathrm{T} \sim u'$ applies
    - Consistent with Damköhler theory
  - Increase of turbulent intensity
    - s_T grows linearly
    - With further increase less than linear



Turbulent Burning Velocity: Thin Reaction Zones

- Reduced increase of turbulent burning velocity
  → second limiting case of Damköhler
- Thin reaction zones/small-scaled turbulence
- In analogy to



Damköhler uses

$$\left.\begin{aligned} s_\mathrm{L} &= \sqrt{\frac{D}{t_\mathrm{c}}} \\[2em] s_\mathrm{T} &= \sqrt{\frac{D_\mathrm{t}}{t_\mathrm{c}}} \end{aligned}\right] \quad \underbrace{\frac{s_\mathrm{T}}{s_\mathrm{L}} = \sqrt{\frac{D_\mathrm{t}}{D}} = \sqrt{\frac{0{,}78\,u'\,l_\mathrm{t}}{s_\mathrm{L}\,l_\mathrm{F}}}}_{\boxed{s_\mathrm{T} \sim \sqrt{u'\,l_\mathrm{t}}}}$$

consistent with experimental data

  - t_c: chemical time scale
  - Dimensional analysis $D_\mathrm{t} \sim u'\,l_\mathrm{t}$
  - Constant of proportionality 0.78

Turbulent Burning Velocity

- Damköhler-limits can be combined to a single formula (Peters, 1999):

$$\frac{s_\mathrm{T}}{s_\mathrm{L}} = 1 - \alpha \frac{l_\mathrm{t}}{l_\mathrm{F}} + \sqrt{\left(\alpha \frac{l_\mathrm{t}}{l_\mathrm{F}}\right)^2 + 4\alpha \frac{u' l_\mathrm{t}}{s_\mathrm{L} l_\mathrm{F}}}$$

  - constant $\alpha = 0{,}195$
- Low turbulence intensity →

$$\frac{s_\mathrm{T}}{s_\mathrm{L}} = 1 + 2 \frac{u'}{s_\mathrm{L}}$$

- High turbulence intensity →

$$\frac{s_\mathrm{T}}{s_\mathrm{L}} = 1 + \sqrt{\frac{0{,}78 u' l_\mathrm{t}}{s_\mathrm{L} l_\mathrm{F}}}$$

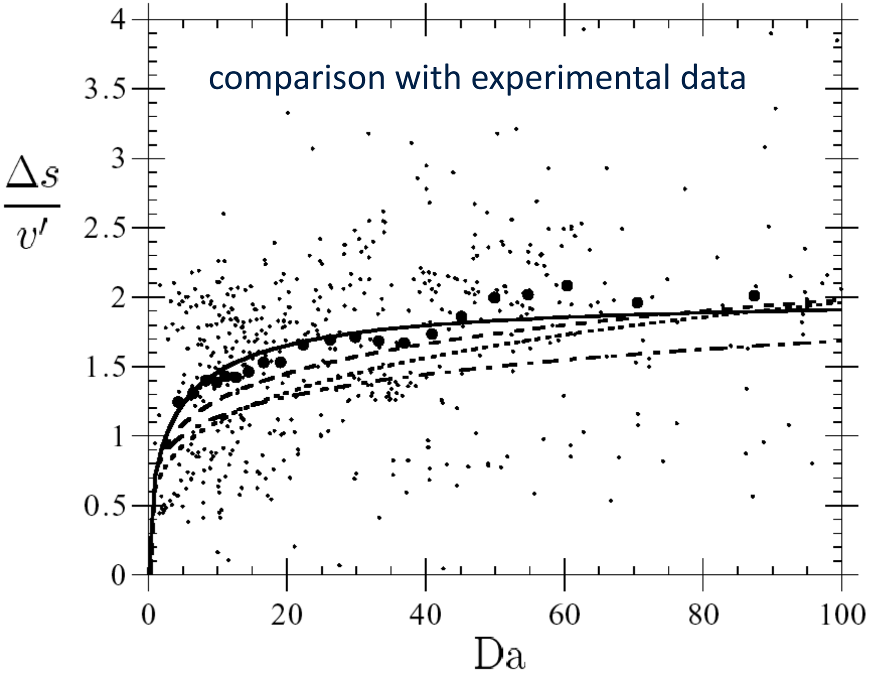
Turbulent Burning Velocity

- By rearranging this formula with $Da_t = (l_t s_L)/(l_F u')$ →

$$\frac{s_T - s_L}{u'} = -\alpha Da_t + \sqrt{\alpha^2 Da_t^2 + 4\alpha Da_t}$$

- Limit for high Damköhler number →

$$\lim_{Da_t \to \infty} \frac{s_T - s_L}{u'} = 2$$



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