Turbulent Premixed Combustion

Combustion Summer School

2018

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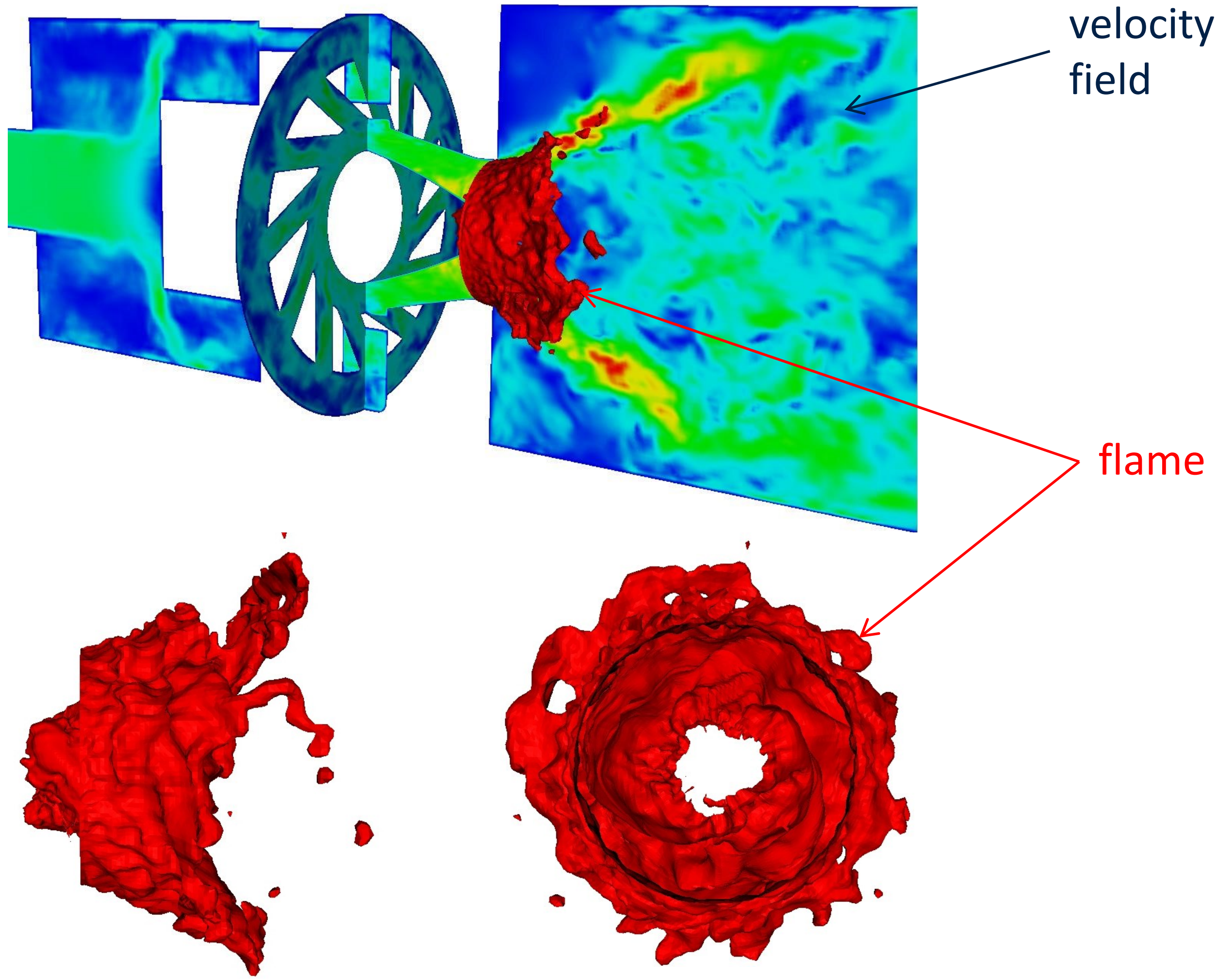
Example: LES of a stationary gas turbine



Course Overview

Part II: Turbulent Combustion

- Turbulence
- Turbulent Premixed Combustion
- Turbulent Non-Premixed Combustion
- Turbulent Combustion Modeling
- Applications

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

Scales of Turbulent Premixed Combustion

- Integral turbulent scales

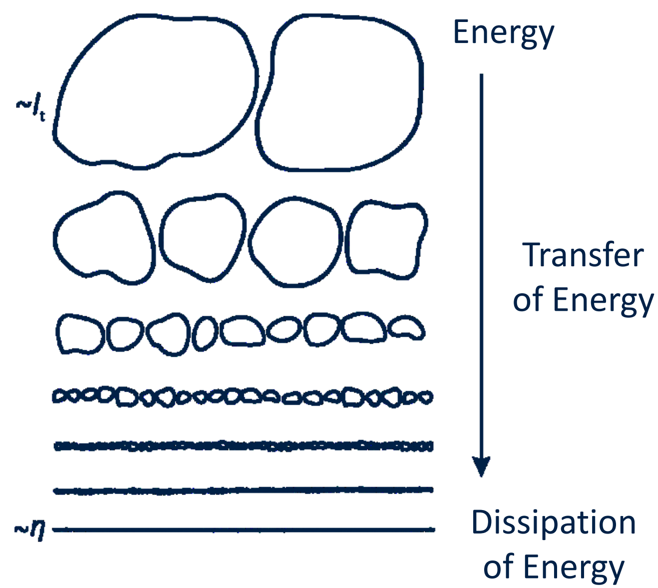
$$l_t = c_1 \frac{\bar{k}^{3/2}}{\bar{\varepsilon}}, \qquad u' = \sqrt{\frac{2}{3}\bar{k}}, \qquad \tau = \frac{l_t}{u'} \sim \frac{\bar{k}}{\bar{\varepsilon}}$$

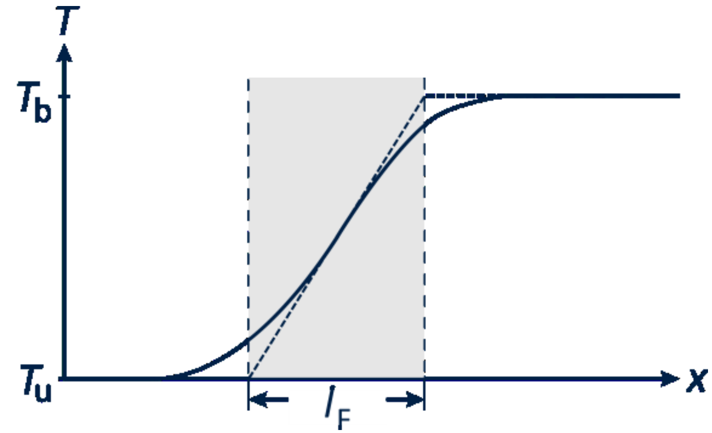
- Smallest turbulent scales/Kolmogorov scales

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

- Flame thickness and time, reaction zone thickness

$$l_F = \frac{D}{s_L} = \frac{\lambda_b}{\rho_u c_p s_L}, \qquad t_F = \frac{l_F}{s_L} = \frac{D}{s_L^2}, \qquad l_\delta \ll l_F$$

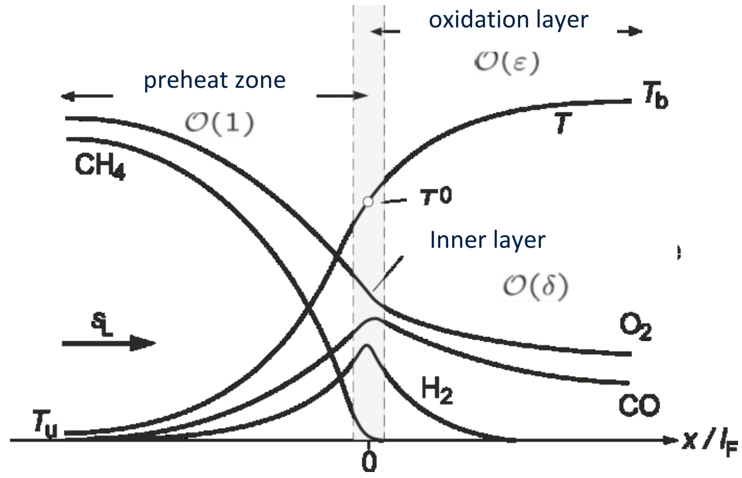




Dimensionless Quantities in Premixed Turbulent Combustion

- Turbulent Reynolds number

$$Sc = \frac{\nu}{D} = 1 \quad \rightarrow \quad Re_t = \frac{l_t}{l_F}\frac{u'}{s_L}$$

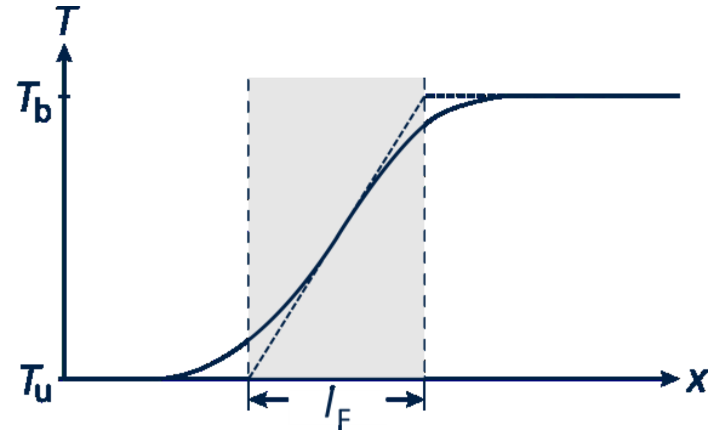


- Turbulent Damköhler number

$$Da_t = \frac{\tau}{t_F} = \frac{l_t}{l_F}\frac{s_L}{u'}$$

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

$$Ka = \frac{t_F}{t_\eta} = \frac{l_F^2}{\eta^2} = \sqrt{\frac{l_F}{l_t}\left(\frac{u'}{s_L}\right)^3} \quad \text{und} \quad Ka_\delta = \frac{l_\delta^2}{\eta^2} = \overset{\delta \approx 0{,}1}{\delta^2} Ka$$



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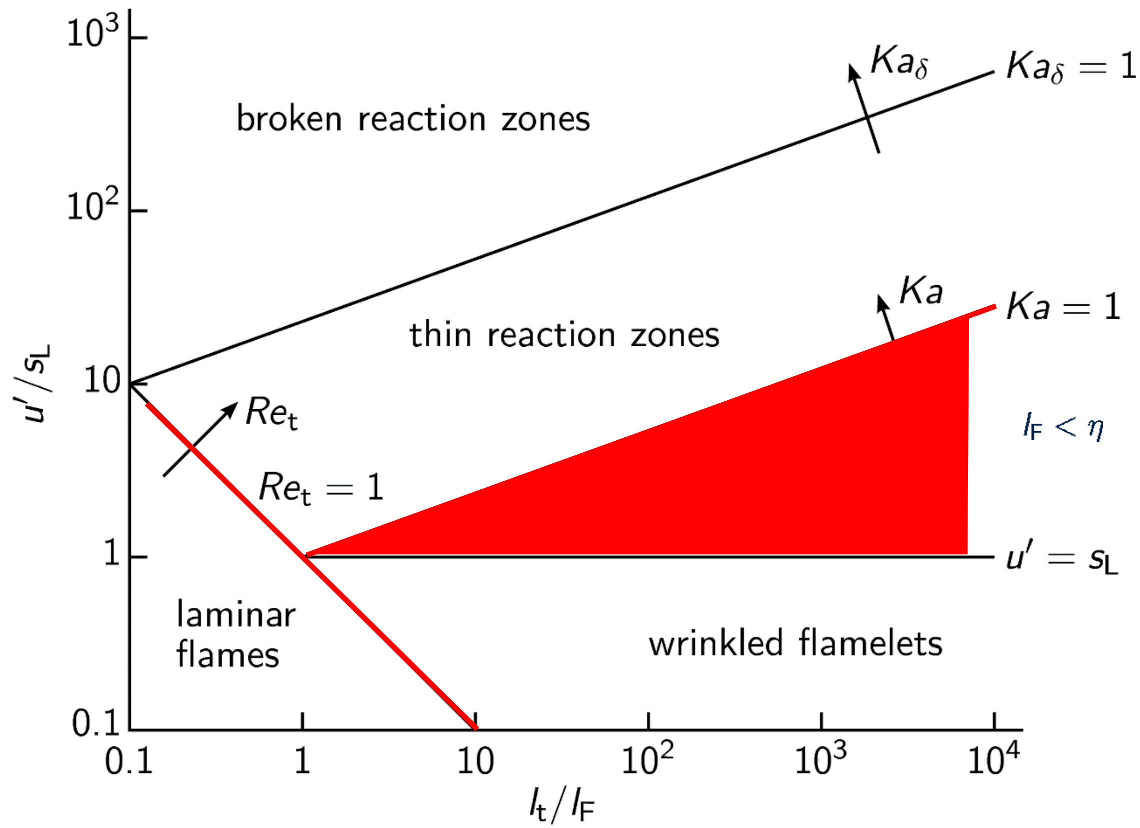
Corrugated Flamelet Regime

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

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

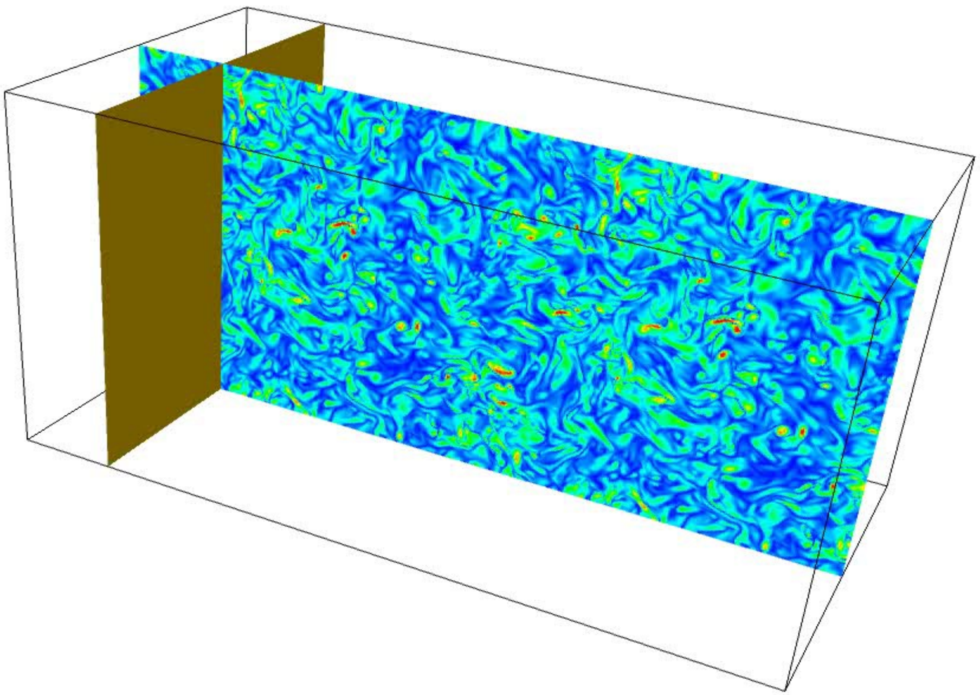
$$Da_t = \frac{l_t}{l_F}\left(\frac{u'}{s_L}\right)^{-1}$$



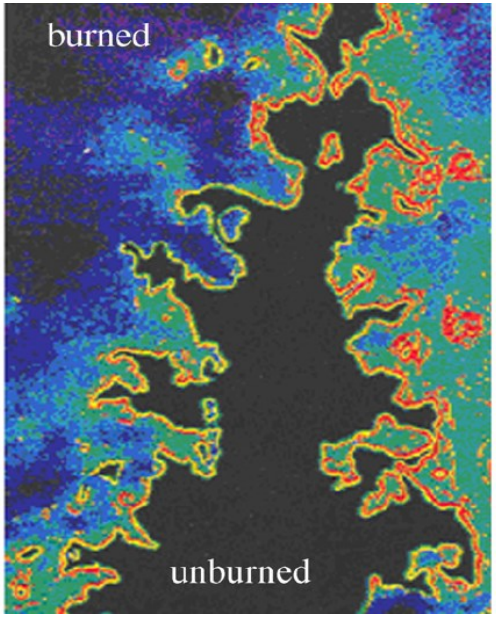
Regime Diagram: Corrugated Flamelets

- $Ka < 1 \rightarrow \eta > l_F$
  - 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)

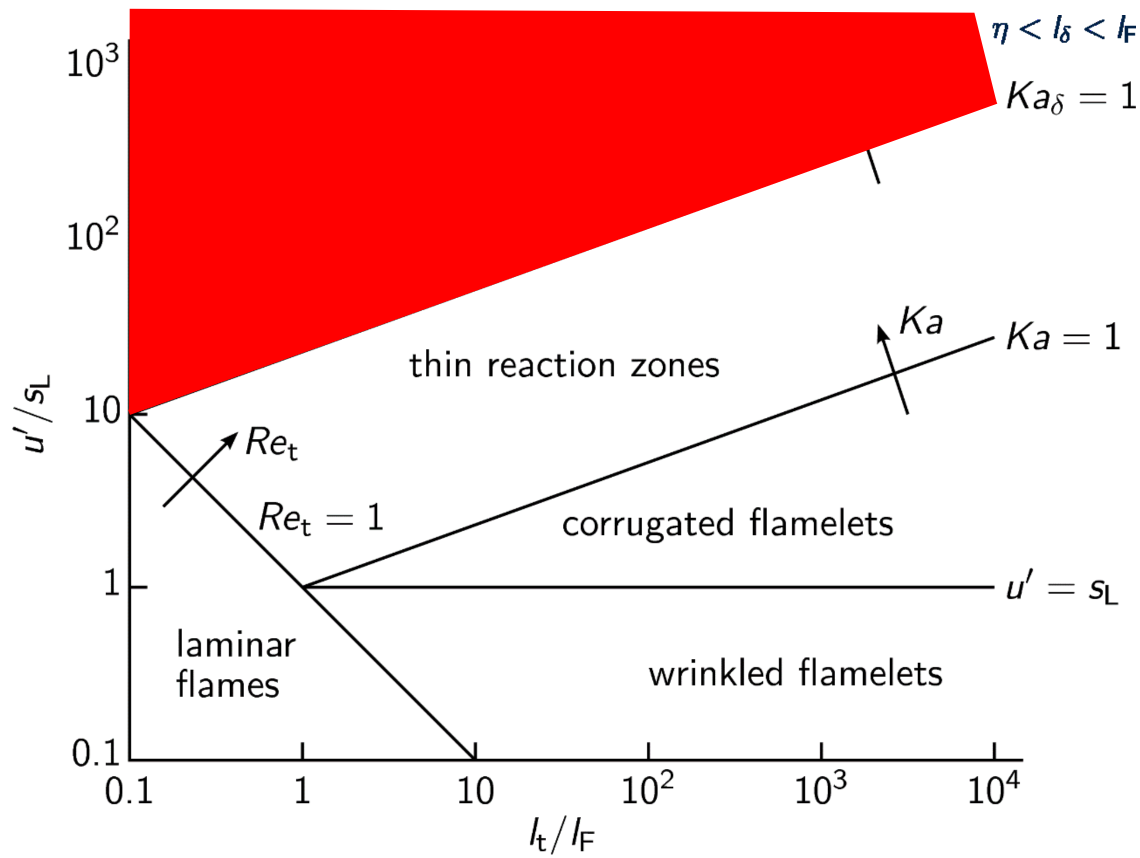
Regime Diagramm: Broken Reaction Zones Regime

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

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

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

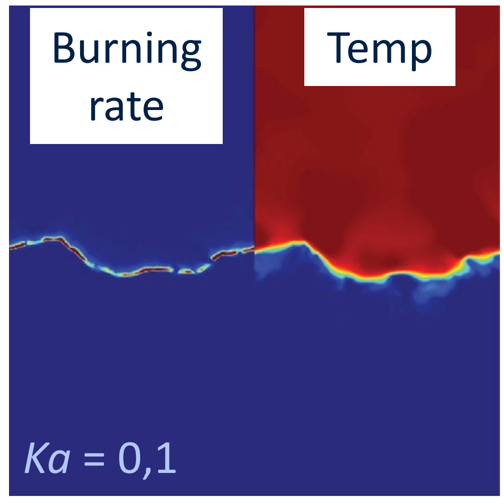
→



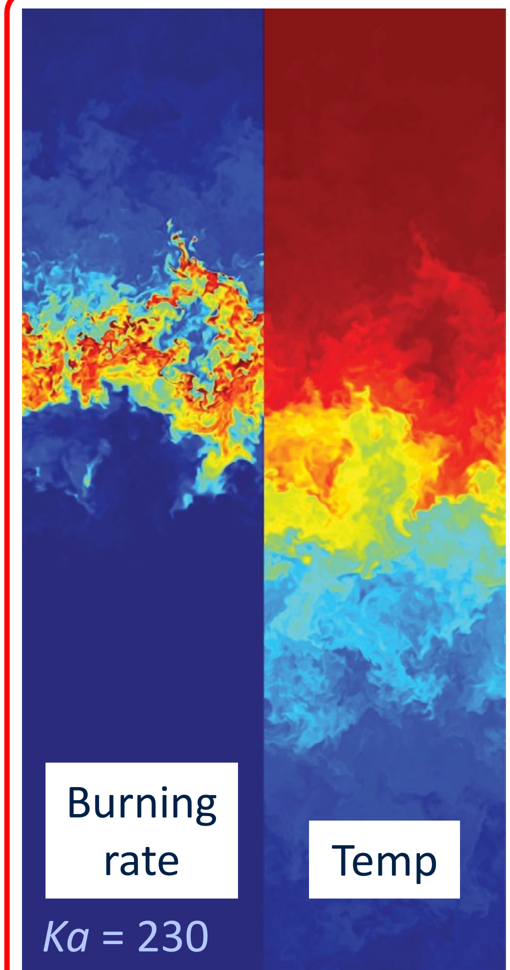
Regime Diagramm: Broken Reaction Zones Regime

- $Ka_\delta > 1 \rightarrow \eta < l_\delta$
  - Smallest turbulent eddies enter the reaction zones
  - Turbulent transport → radicals are removed from reaction zone
  - Local extinction in the inner reaction zone possible
    - Can lead to global flame extinction

Example: Supernovae flames with transport mechanisms very different from normal flames



Two-dimensional slices from three-dimensional simulations



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

Regime Diagramm: Thin Reaction Zones Regime

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

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

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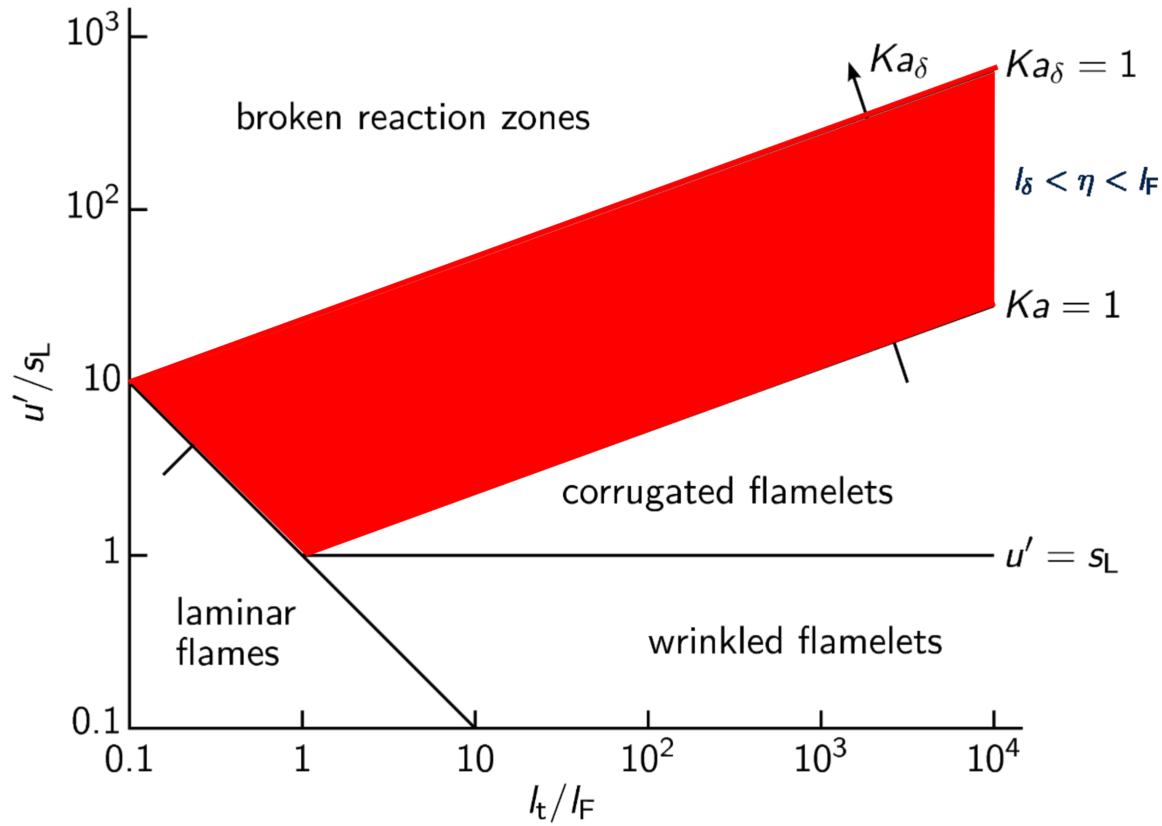
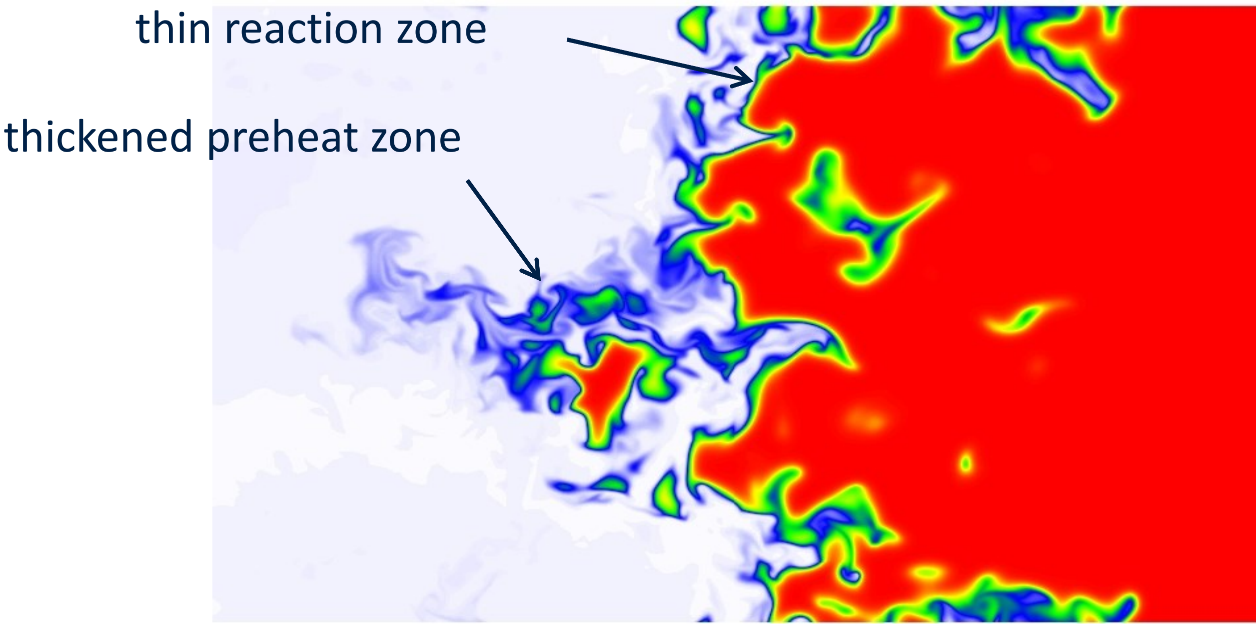


Regime Diagramm: Thin Reaction Zones Regime

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

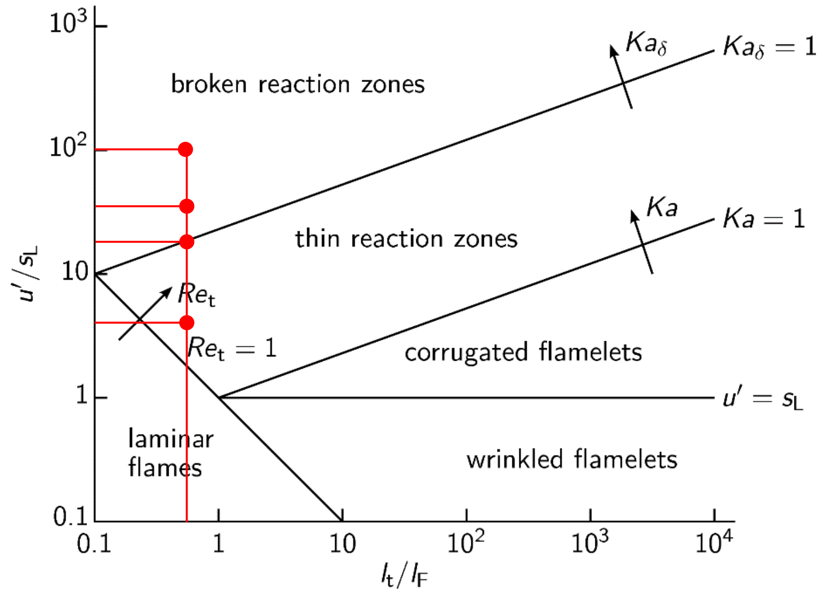


temperature distribution from DNS of a premixed turbulent flame

Regime Diagram: Summary

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}
RMS velocity ($\check{u}$) ($\mathrm{m\,s^{-1}}$)	0.825	3.83	7.34	23.9
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: Summary

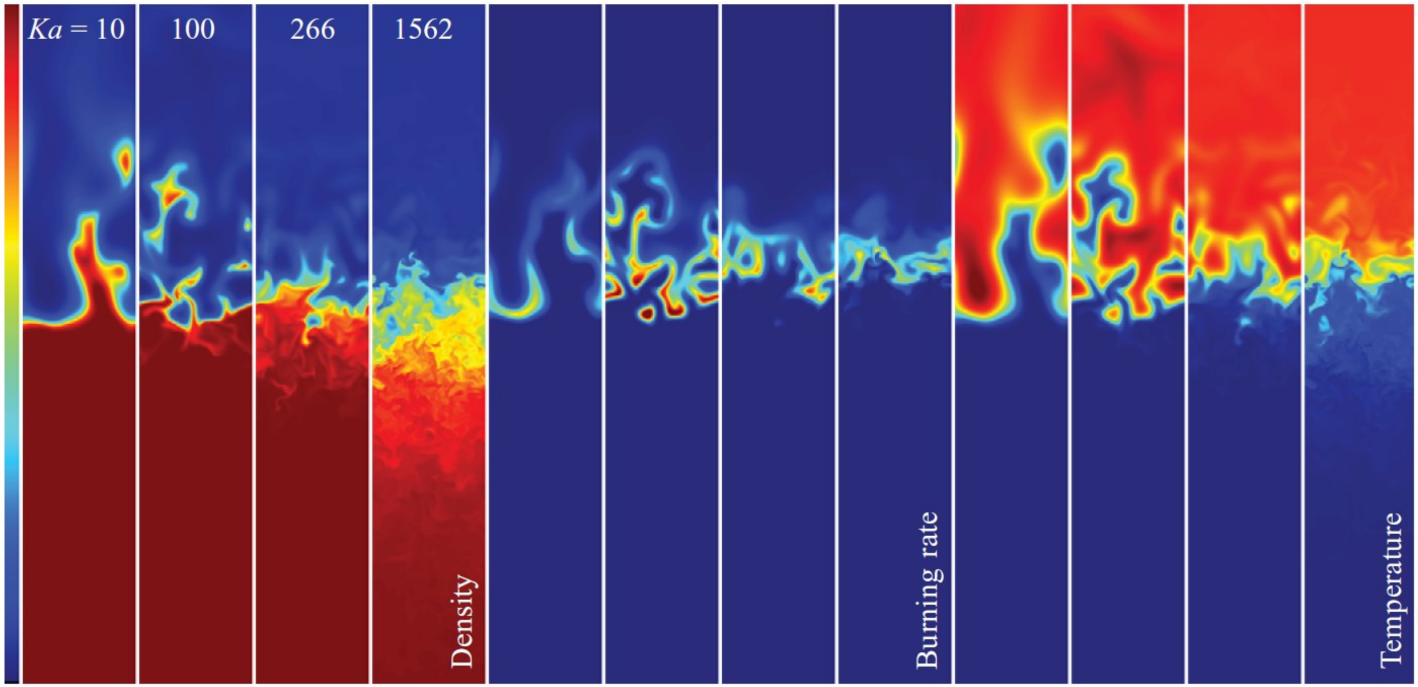
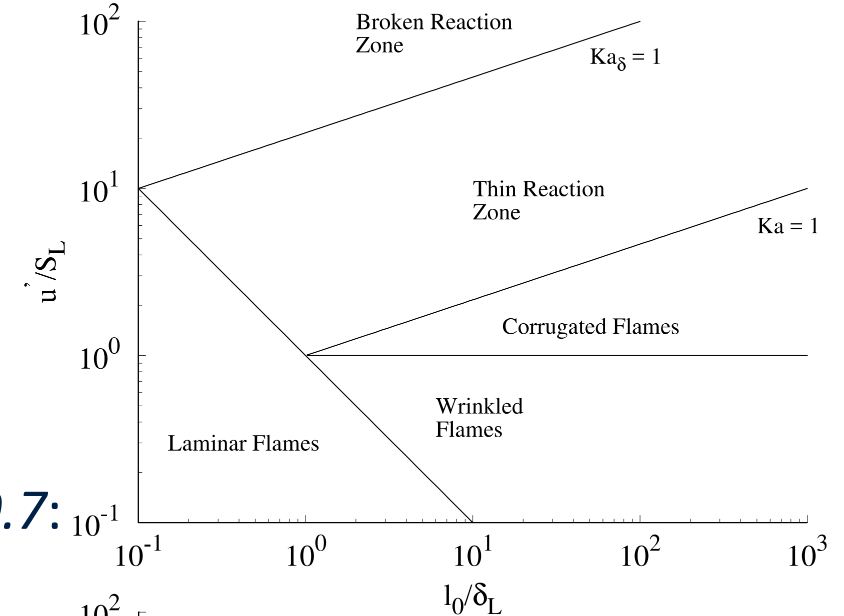


FIGURE 8. Two-dimensional vertical slices through three-dimensional simulations showing density, burning rate and temperature at $\varphi = 0.40$, respectively. The density, burning rate and temperature ranges are [0.2,1.02] kg m^{-3}, [0,64] kg m^{-3} s^{-1} and [298,1600] K, respectively.

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

Regime Diagram: Corrections from Ideal Scaling

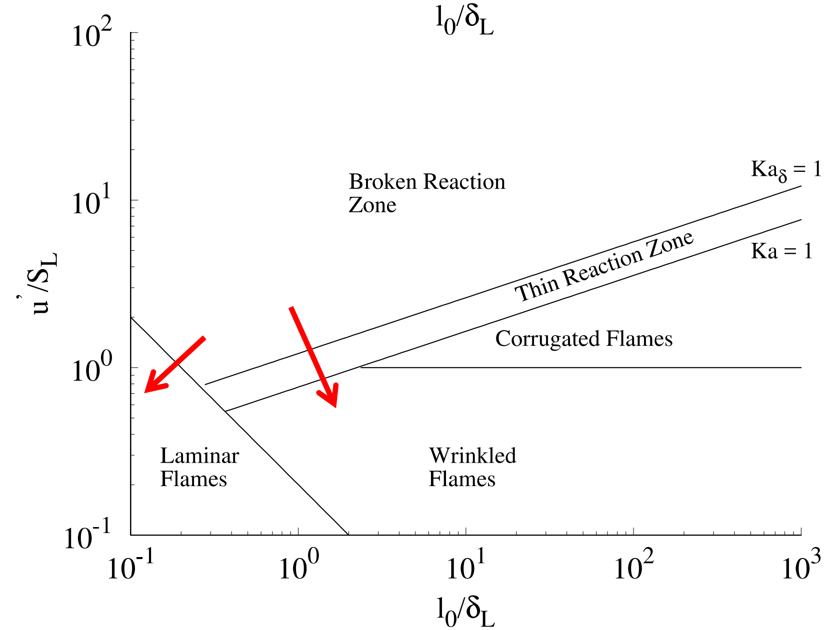
- Usual assumptions:
  - $Sc = 1 \rightarrow \nu = D$
  - $S_L l_F / \nu \approx 1$
  - $l_\delta \approx 0{,}1 l_F \rightarrow Ka \approx 100 Ka_\delta$



- Example: Methane/air flame, $T_u = 800K$, $\varphi = 0.7$:
  - $Sc \approx 1 \rightarrow \nu \approx D$

  but

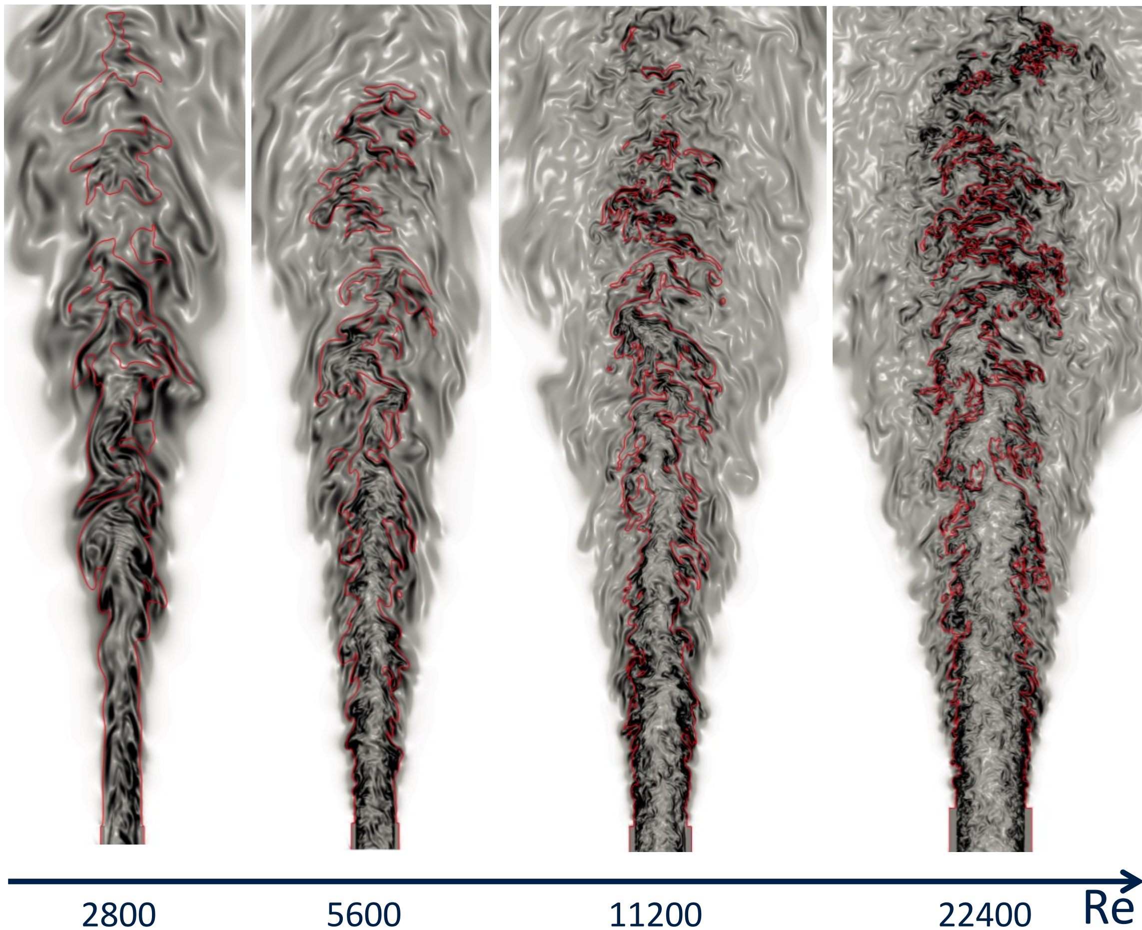
  - $S_L l_F / \nu \approx 5$
  - $l_\delta \approx 0{,}5 l_F \rightarrow Ka \approx 4 Ka_\delta$



Lines only for scaling,
be careful with absolute values

DNS at Constant Ka for Various Re

- Lean methane flame T_u=800K, φ=0.7 (S_L=1m/s)
- ***Re variation: constant u' and increased l_t → constant Karlovitz (approximately)***



(from A. Attili et al, 2017)

Re	2800	5600	11200	22400
Ka	40	40	40	40
U_{bulk}	100 m/s	100 m/s	100 m/s	100 m/s
u'	10 m/s	10 m/s	10 m/s	10 m/s
Jet widths	**0.6 mm**	**1.2 mm**	**2.4 mm**	**4.8 mm**
Grid points	88 Million	350 Million	2.8 Billion	22 Billion

DNS at Constant Ka for Various Re

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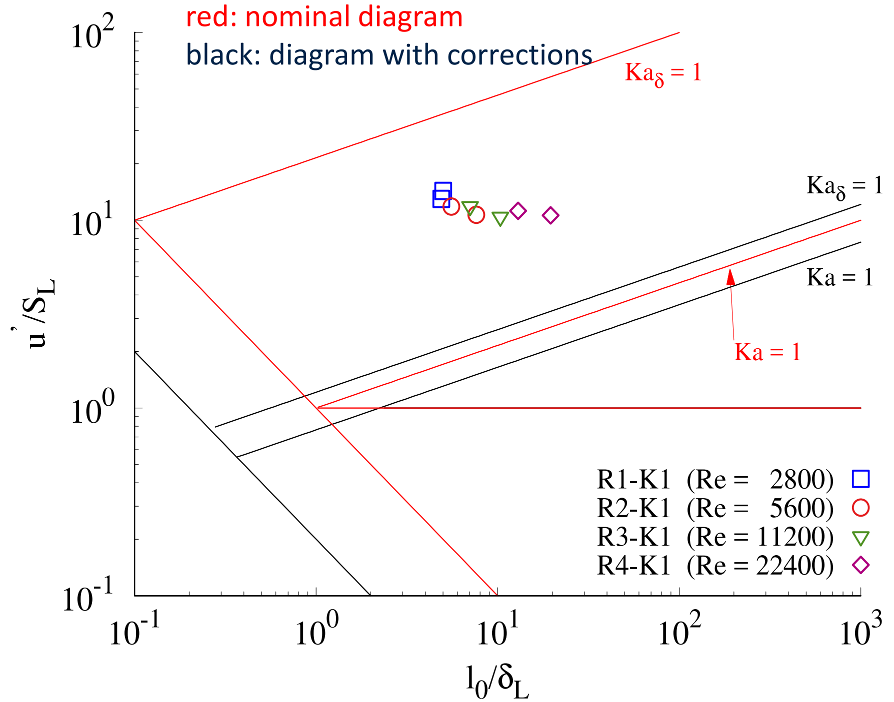


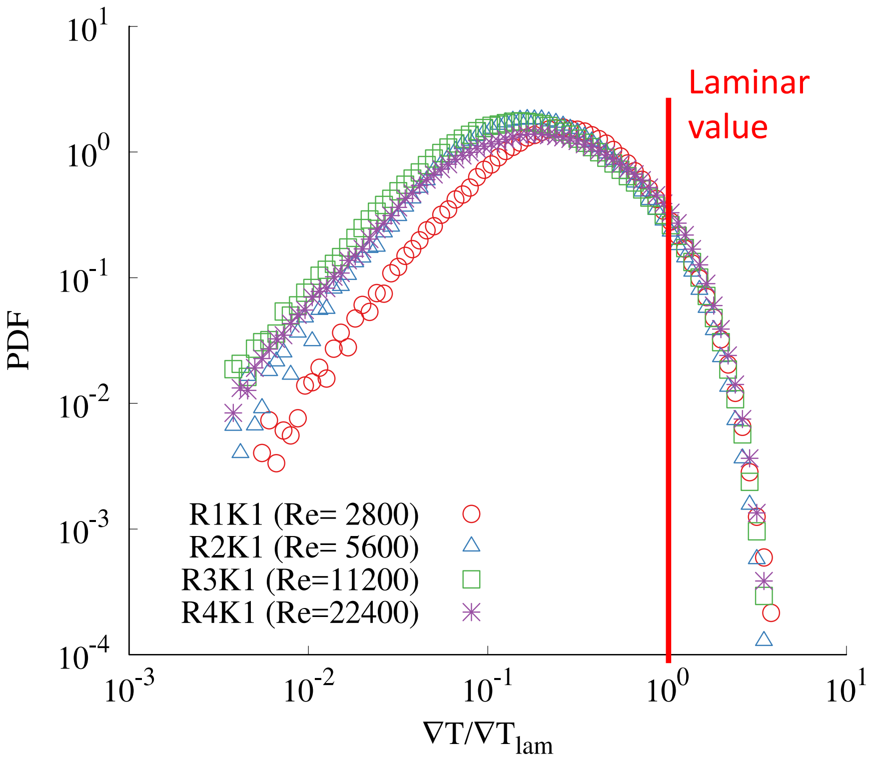
- Reynolds number changed by jet width *H*
- *L_t ~ H*
- $\eta = l_t\, Re_t^{-3/4} \sim l_t^{1/4}$, hence η increases slightly with increasing *H*

Not clear in which regime the flames are

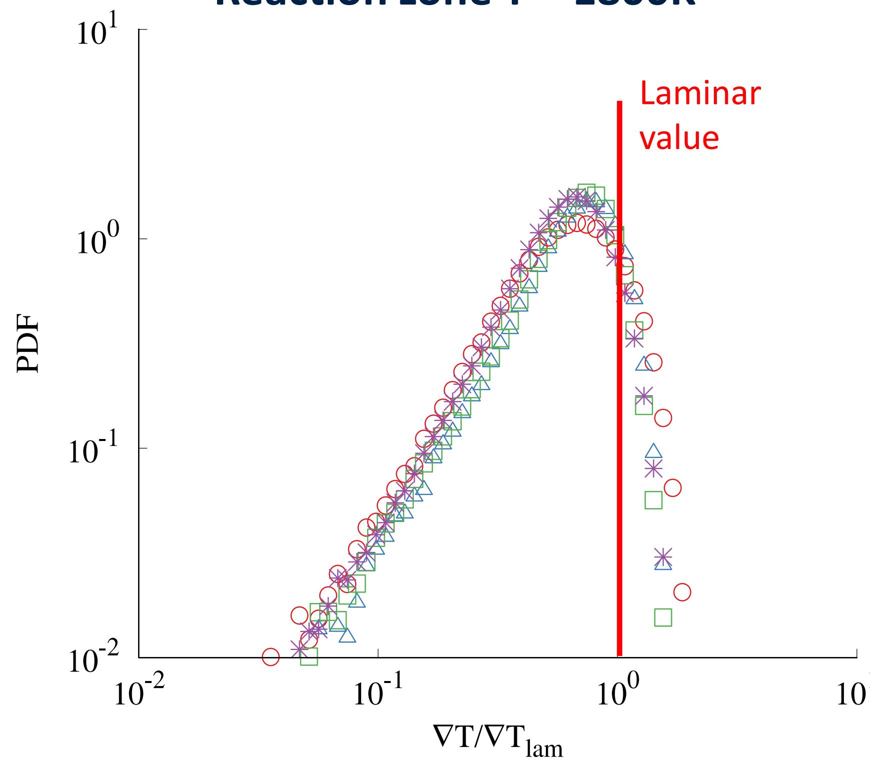
- Thin reaction zone
- Broken reaction zone

Different Re and constant Ka DNS: regime assessment

Preheat zone T = 900K



Reaction zone T = 1800K

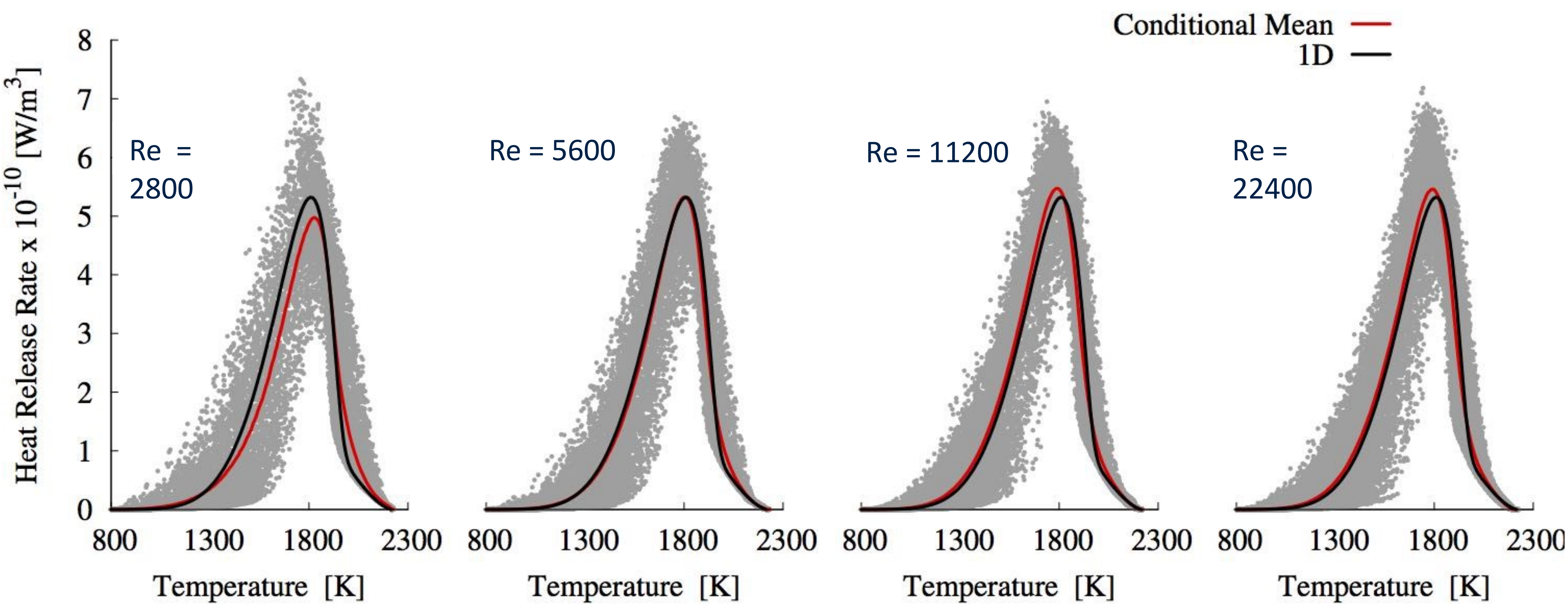


- Strong turbulent mixing in the preheat zone
  - gradient PDF is wide
  - PDF close to log normal (typical for gradients in turbulence)
  - far from the gradient in a laminar 1D flame

- Reaction zone not affected by change in turbulence
  - gradient PDF is narrow
  - close to the gradient in laminar unstretched 1D flame

The flames are in the thin reaction zone regime

Different Re and constant Ka DNS: flame structure



- Flame structure very similar to 1D laminar flame
  - Conditional mean from DNS agrees well with 1D flame profile
  - Small scatter
- **Reynolds number effects** are related to **different transport in the preheat zone**, not to modifications of the flame structure

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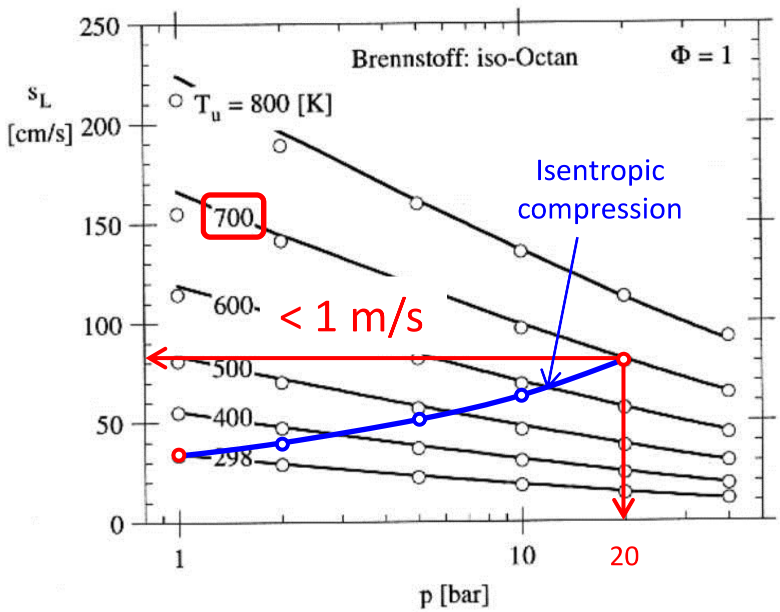
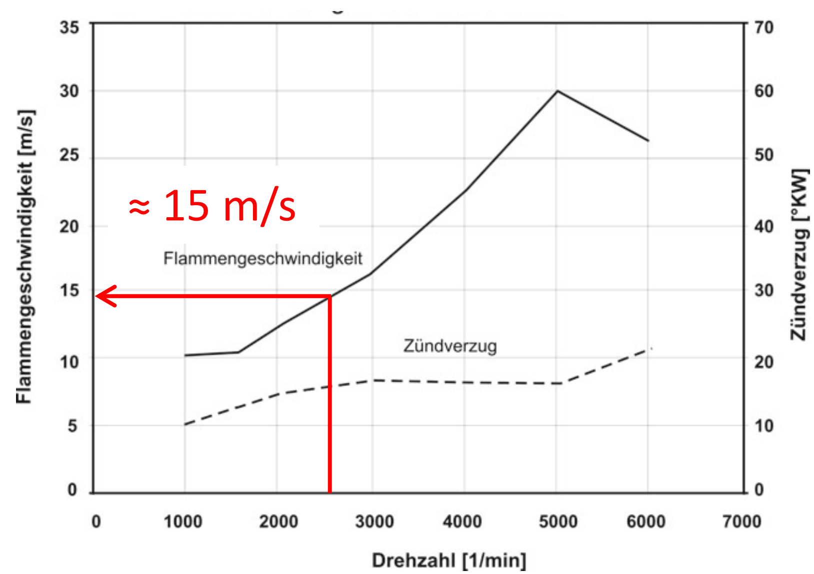
Turbulent Burning Velocity

Comparison: Laminar/Measured Burning Velocity

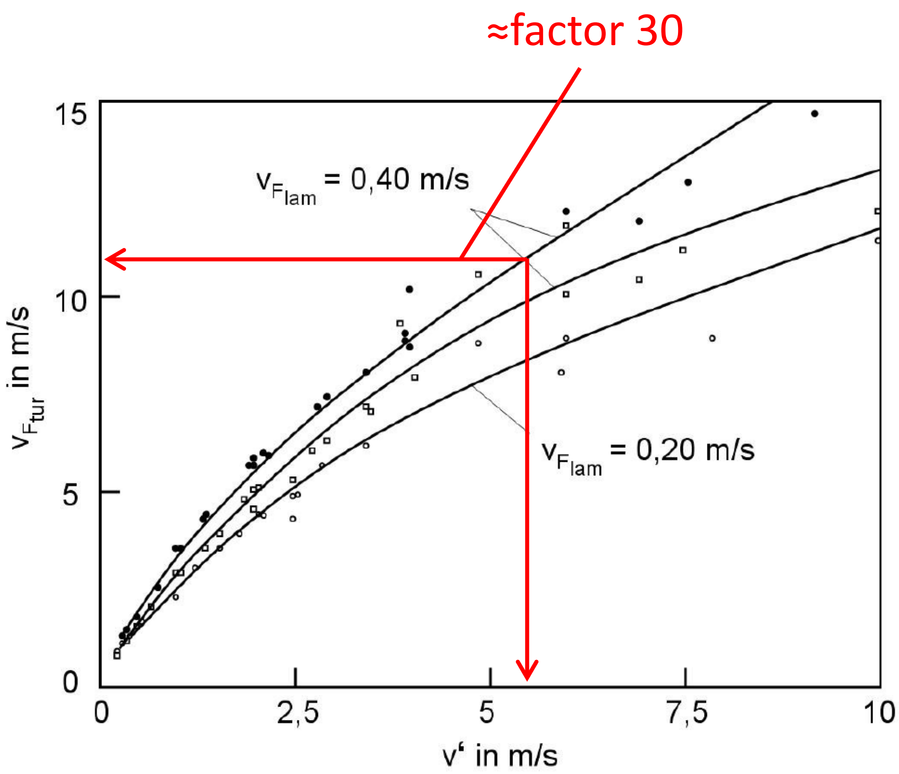


Laminar burning velocity
of iso-octane



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

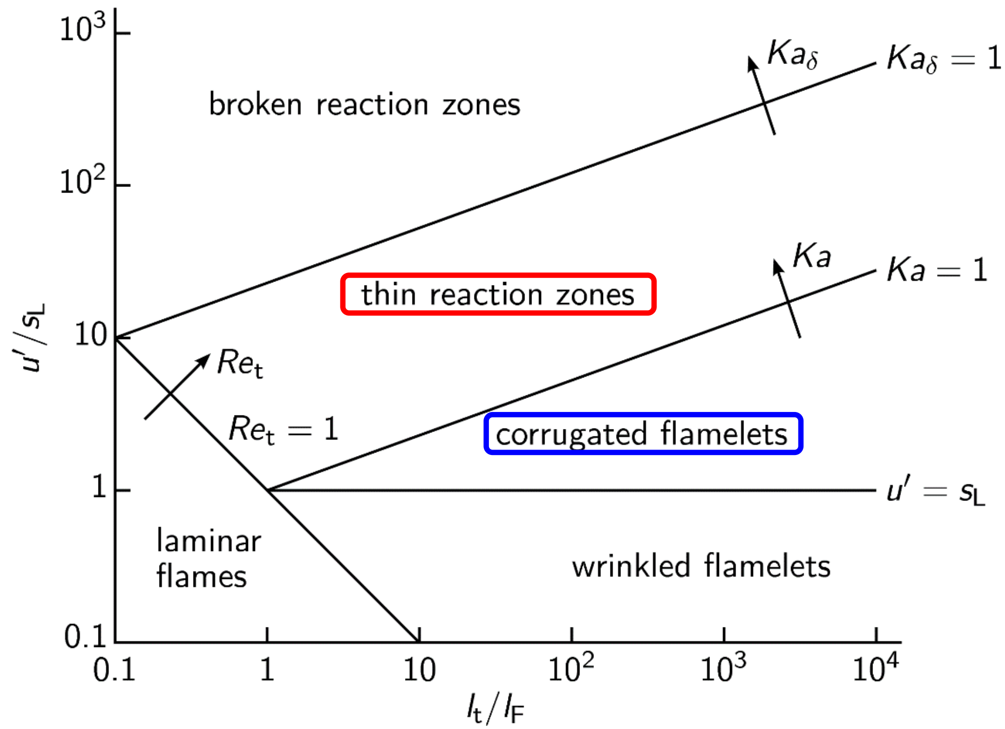
Comparison: Laminar/Measured Burning Velocity



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

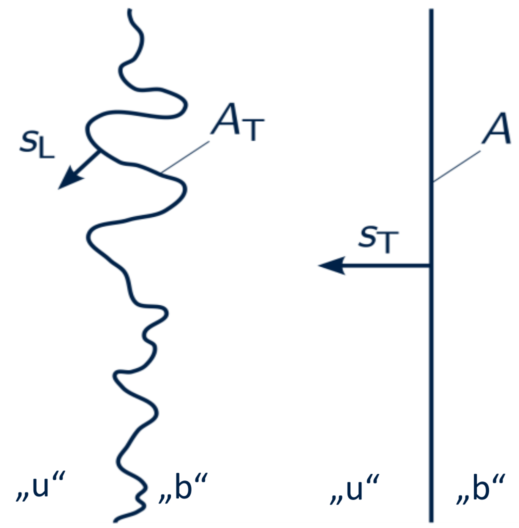
Turbulent Burning Velocity

- 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 $\leftrightarrow$ corrugated flamelets
  2. Small scale turbulence $\leftrightarrow$ 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

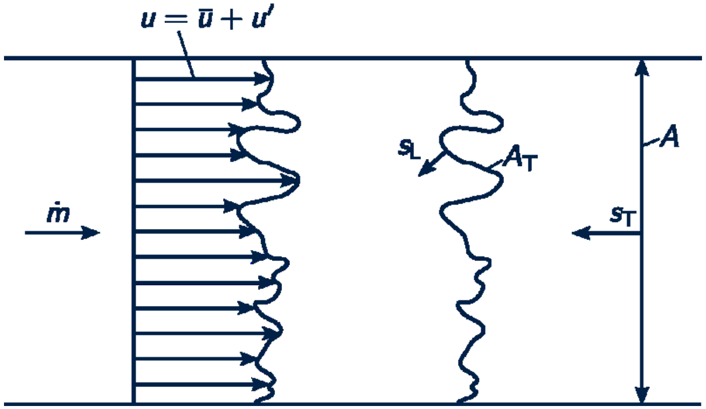
- With the mass flux trough A and A_T

[redacted]

- Assume constant density in the unburnt mixture (assumption) [redacted]

$$\boxed{\frac{s_T}{s_L} = \frac{A_T}{A}}$$

- Wrinkling of the laminar flame ($A_T \uparrow$) → increase of s_T



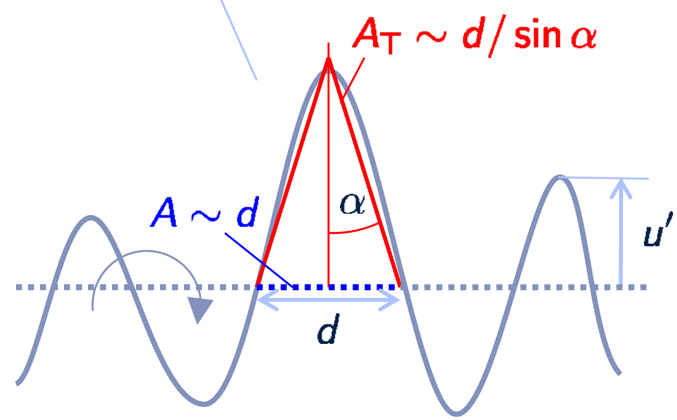
Turbulent Burning Velocity: Corrugated Flamelets

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

$$s_L = u_u \sin\alpha \quad \xrightarrow{\text{hier}} \quad \sin\alpha = \frac{s_L}{u'} \quad \Rightarrow \quad \frac{A_T}{A} \sim \frac{d/\sin\alpha}{d} = \frac{u'}{s_L}$$

- Limit for $u' \rightarrow 0$

$$\boxed{\frac{s_T}{s_L} = \frac{A_T}{A} = 1 + \frac{u'}{s_L}}$$



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

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

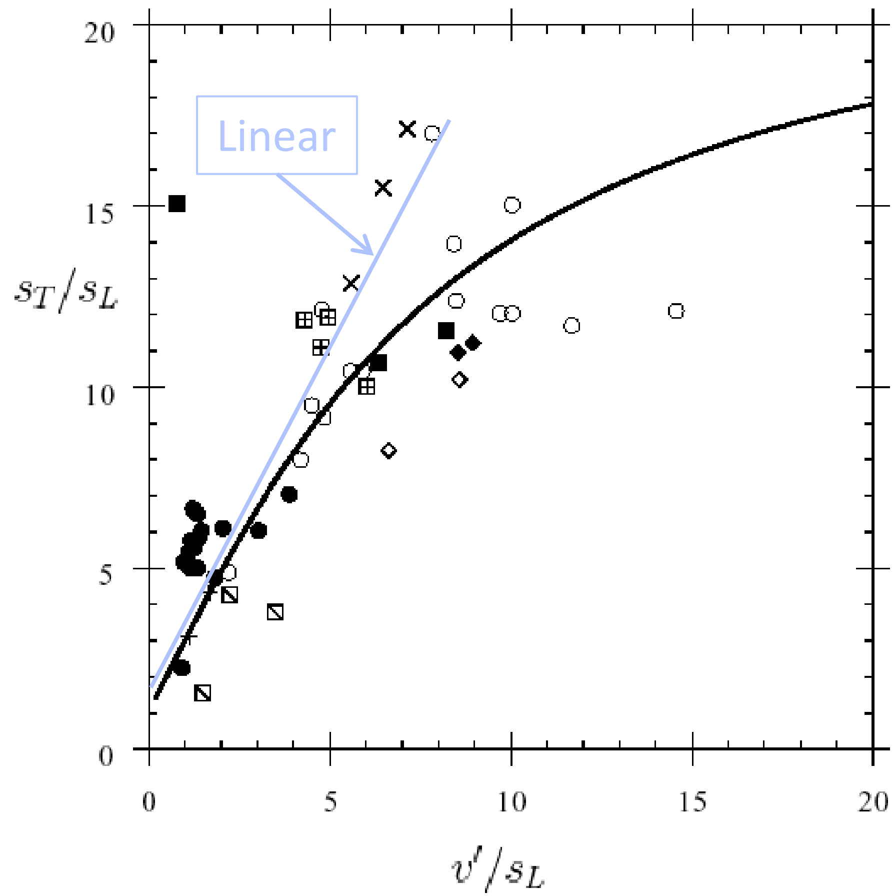
→ High engine speed achievable

Turbulent Burning Velocity: large-scale turbulence

- In experiments often used empirical relation

$$\frac{s_T}{s_L} = 1 + C\left(\frac{u'}{s_L}\right)^n$$

  - Constant C experimentally determined
  - Typical values: $0.5 < n < 1.0$
- From experimental data →
  - For small u', $s_T \sim u'$ 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

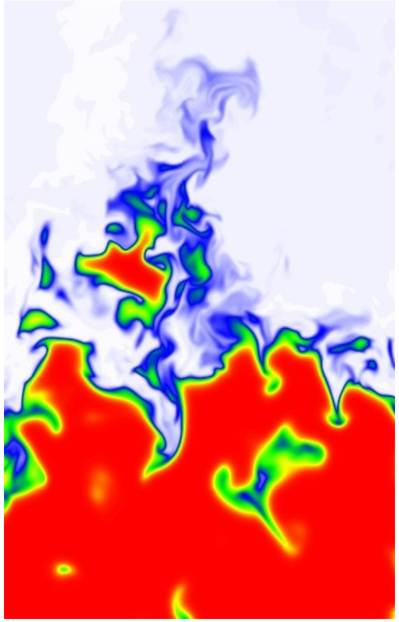
- Reduced increase of turbulent burning velocity
  → second limiting case of Damköhler
- Thin reaction zones/small-scaled turbulence
- In analogy to

Damköhler uses

$$\left.\begin{aligned} s_L &= \sqrt{\frac{D}{t_c}} \\ s_T &= \sqrt{\frac{D_t}{t_c}} \end{aligned}\right\} \quad \underbrace{\frac{s_T}{s_L} = \sqrt{\frac{D_t}{D}} = \sqrt{\frac{0{,}78\,u' l_t}{s_L l_F}}}$$

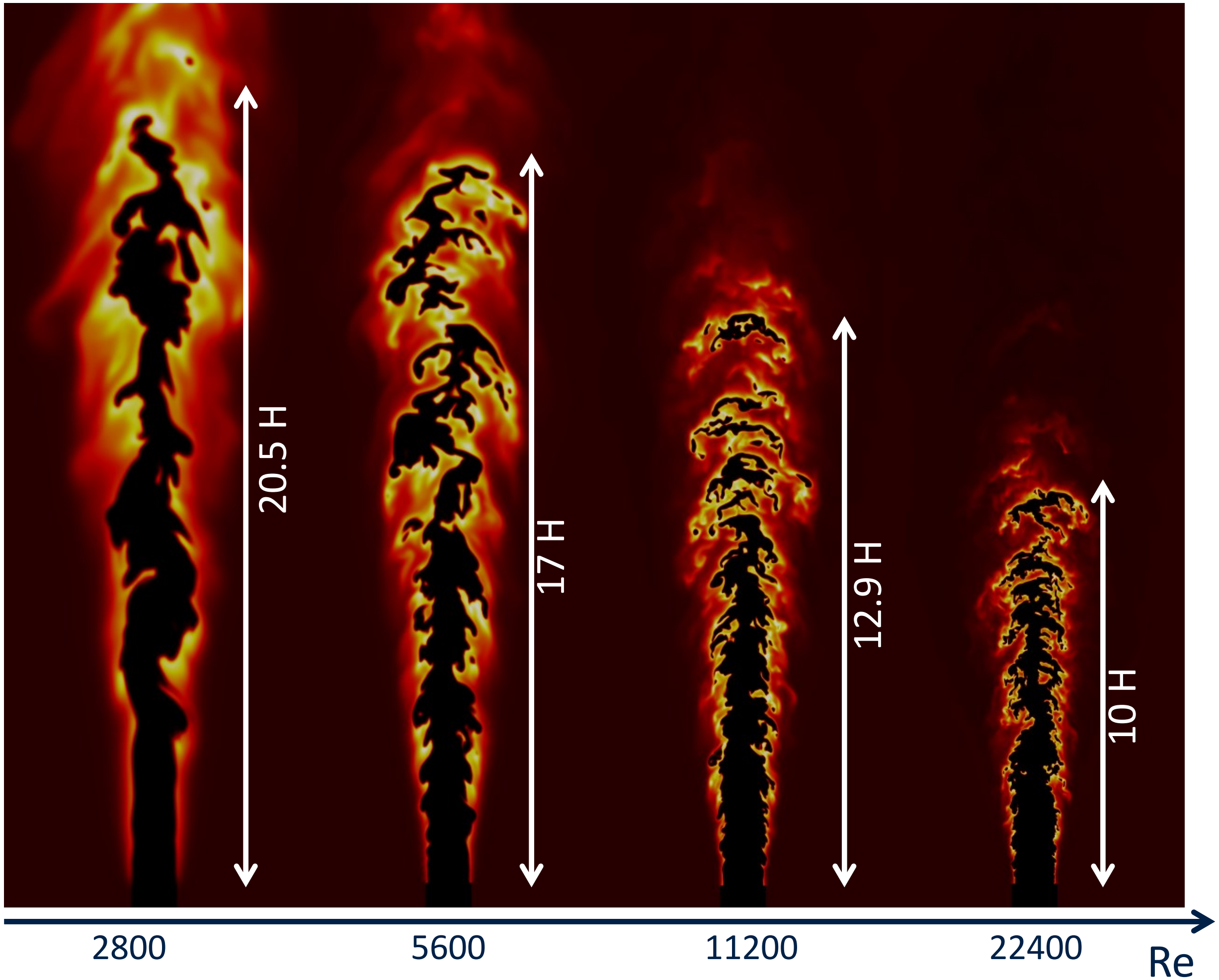
$$\boxed{s_T \sim \sqrt{u' l_t}}$$

consistent with experimental data

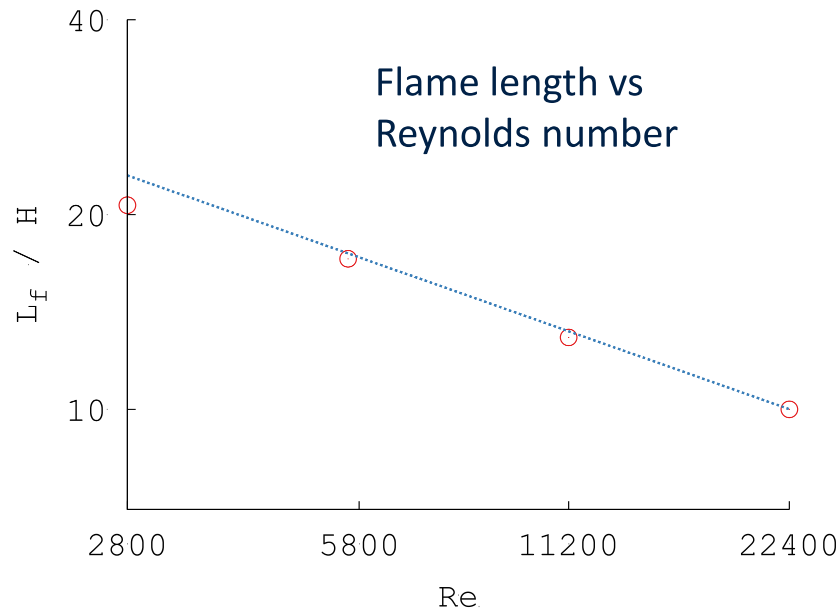


- t_c: chemical time scale
- Dimensional analysis $D_t \sim u' l_t$
- Constant of proportionality 0.78

Turbulent Burning Velocity: Thin Reaction Zones



(from A. Attili et al, 2017)



- Decreased length → increased flame speed
- Turbulent flame speed increases with increasing Reynolds number
  - u' is constant
  - Increased flame speed due to increased integral scale

Turbulent Burning Velocity

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

$$\frac{s_T}{s_L} = 1 - \alpha \frac{l_t}{l_F} + \sqrt{\left(\alpha \frac{l_t}{l_F}\right)^2 + 4\alpha \frac{u' l_t}{s_L l_F}}$$

  - constant α = 0,195
- Low turbulence intensity →

$$\frac{s_T}{s_L} = 1 + 2\frac{u'}{s_L}$$

- High turbulence intensity →

$$\frac{s_T}{s_L} = 1 + \sqrt{\frac{0{,}78 u' l_t}{s_L l_F}}$$

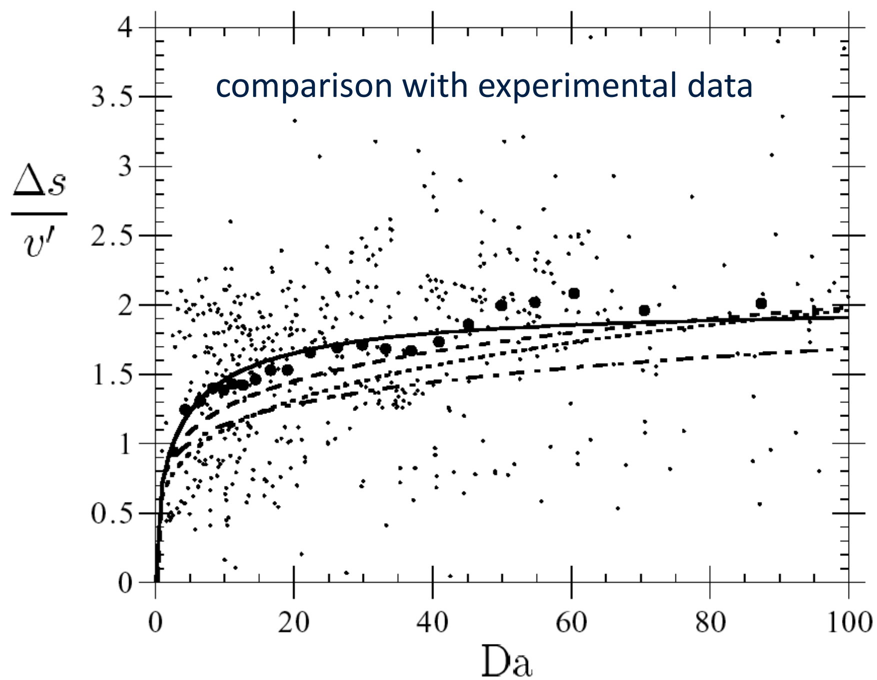
Turbulent Burning Velocity

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

[redacted]

- Limit for high Damköhler number →

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



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