Content of Lecture

OTTO VON GUERICKE
UNIVERSITÄT
MAGDEBURG

1. Phenomenology of Combustion
2. Thermodynamic Fundamentals
3. Chemical Reaction Kinetics
4. Ignition and Ignition Limits
5. Laminar Flame Theory
6. Turbulent Combustion
7. Pollutants of Combustion
8. Combustion of Liquid and Solid Fuels
9. Numerical Simulation
10. Measurement Techniques of Combustion Processes
11. Applied Aspects of Turbulent Combustion
12. Technical Burner Systems
13. Internal Combustion Engines

Contents

6. Fundamentals of turbulent combustion

6.0 Motivation for turbulent combustion

6.1 Turbulence quantities

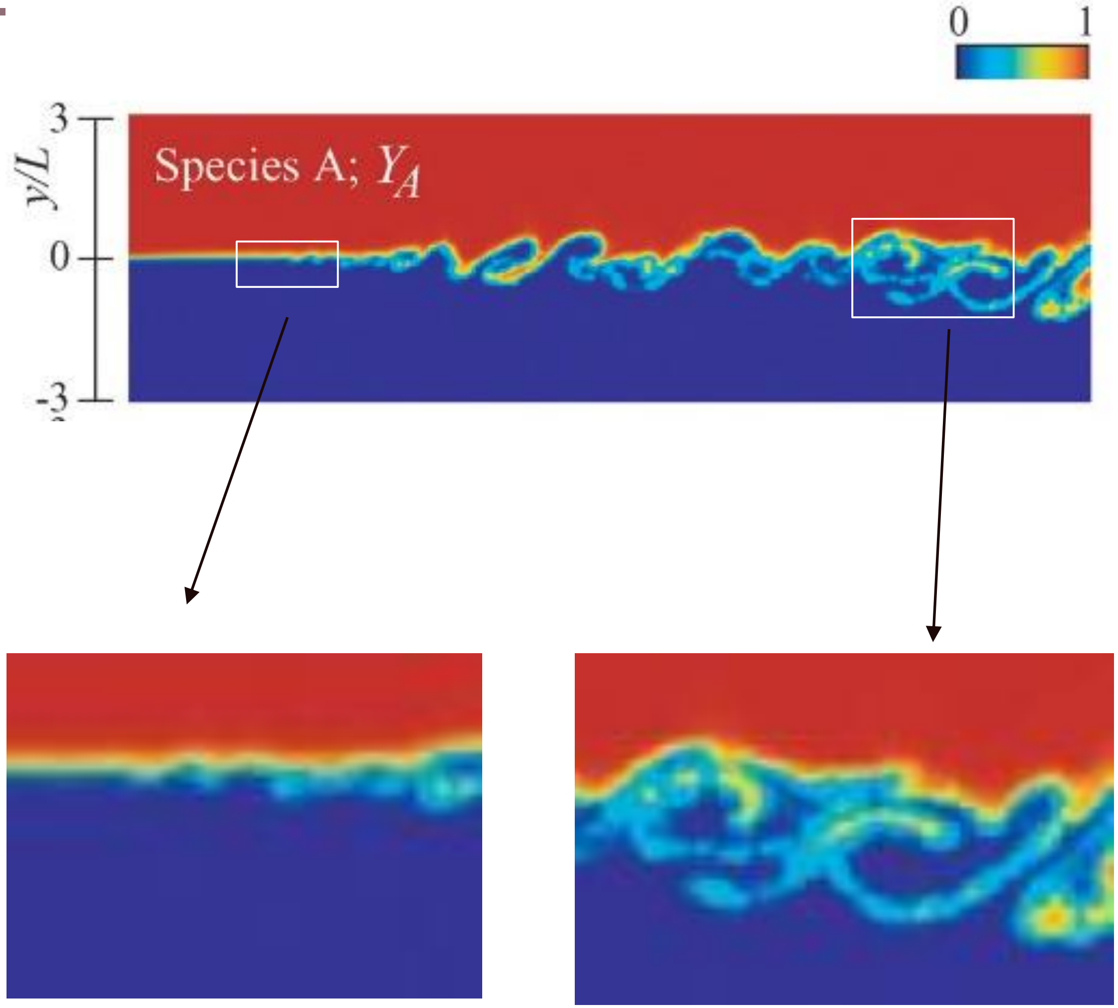
6.2 Turbulent premixed flames

- The Borghi diagram
- Structure of turbulent flames
- Turbulent flame speed
- Approaches for calculation

6.3 Turbulent diffusion flames

- Examples
- Flame length
- Concept of mixture fraction

Motivation for turbulent combustion



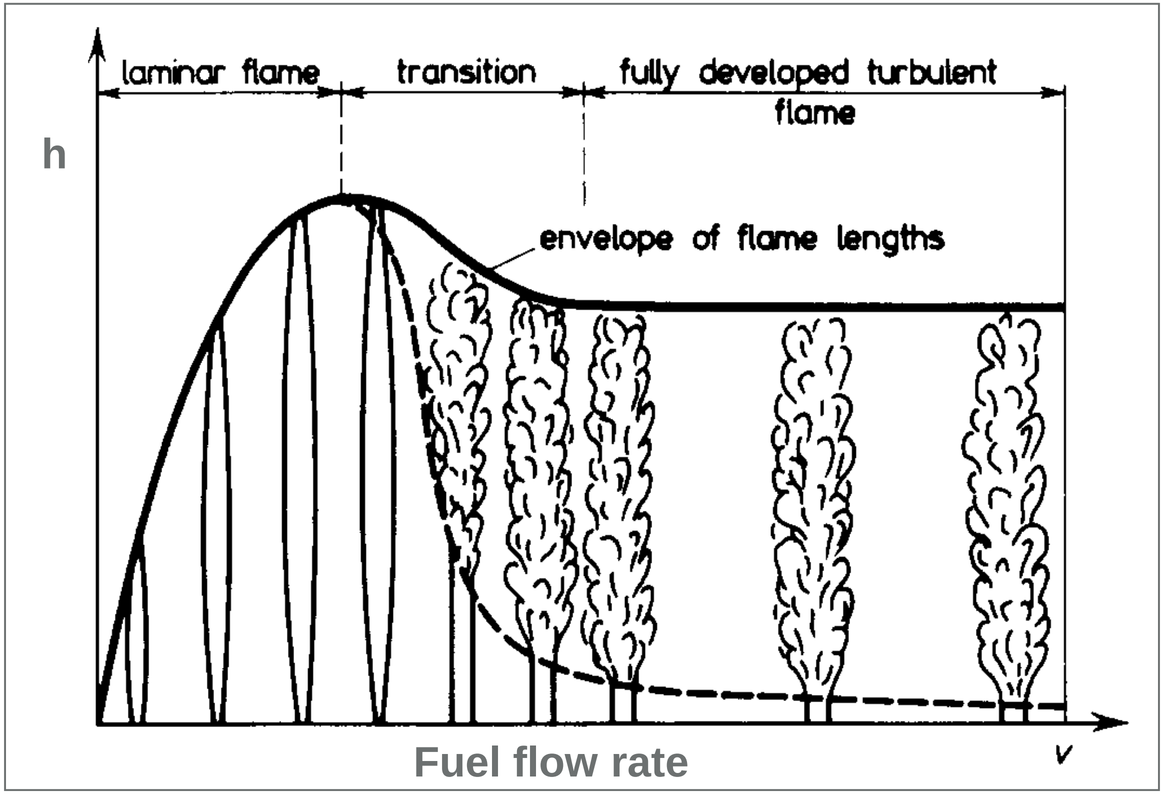
- Two flows of two species at different velocities behind splitter plate
- Shear at interface lead to formation of eddies, which grow.
- Fluid B convected upward, and Fluid A convected downward
- Interfacial area over which diffusion occurs is increased ->enhanced mixing

Tomomi Uchiyama, Nagoya University Japan

6.0 Motivation for turbulent combustion

Why turbulent combustion ?

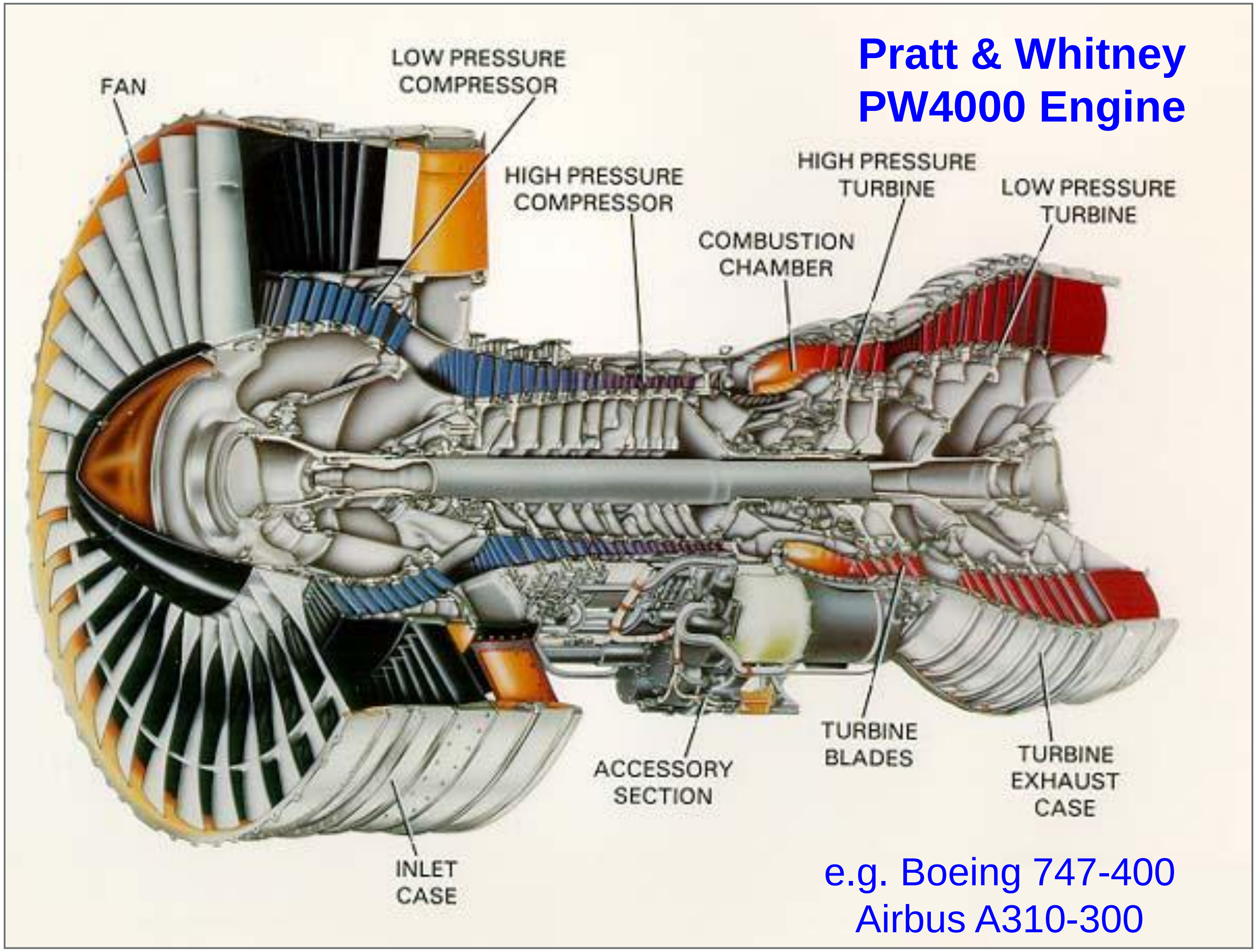
- Mixing is enhanced → Heat release per volume (power density) increases → smaller burning chambers possible (engine, airplane engine)



foll. Hottel u. Hawthorne, 3. Comb. Symp. (1949)

Motivation for turbulent combustion

Why turbulent combustion ?



Pratt & Whitney PW4000 Engine

e.g. Boeing 747-400
Airbus A310-300

Turbulence quantities

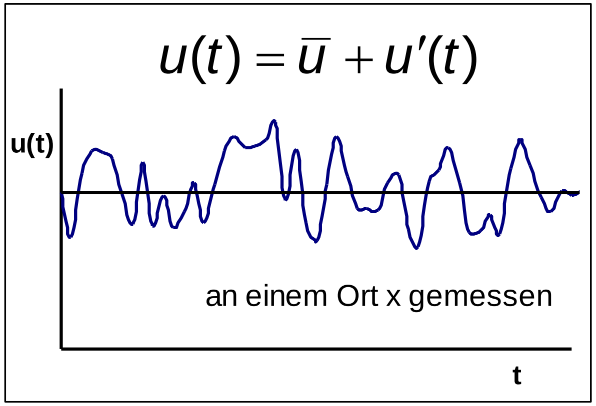
6.2 Turbulence Quantities

Turbulent Flow:

- time dependent fluctuating velocities
- three dimensional
- eddy structures (e.g. *Karman's eddy street*)

2 possible approaches:

- statistical
  - -> Mean value
  - -> Standard deviation etc.
- structural
  - eddy description, LES, DNS



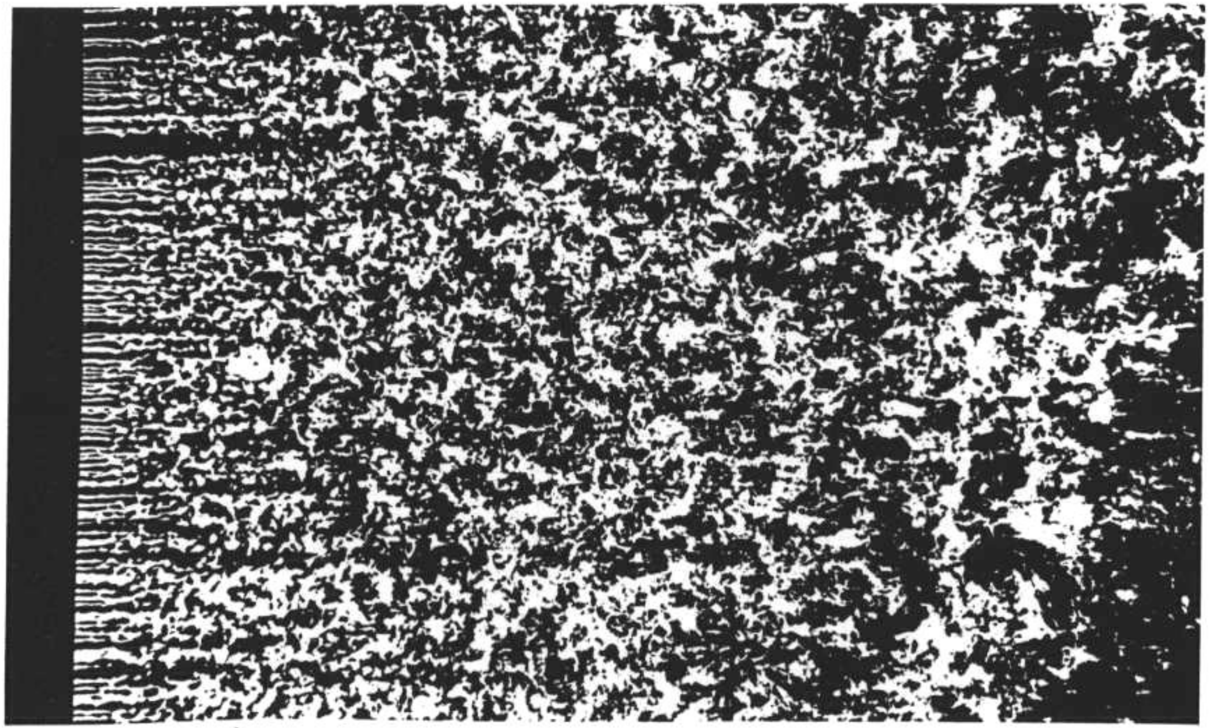
$$u(t) = \overline{u} + u'(t)$$

Turbulence quantities

Homogeneous Turbulence

Idealization: Homogeneous isotropic turbulence (assumed in the following)

- In reality only as approximation:
- 1: Stirred chamber with strong mixing without swirl
- 2: "Grid turbulence " = "Wind channel turbulence"



153. Homogeneous turbulence behind a grid. Behind a finer grid than above, the merging unstable wakes quickly form a homogeneous field. As it decays downstream, it provides a useful approximation to the idealization of isotropic turbulence. *Photograph by Thomas Corke and Hassan Nagib*

Turbulence quantities

Homogeneous Turbulence

Common statistical approach: Reynolds decomposition

Mean value

$$u(t) = \bar{u} + u'(t) \qquad (6.1)$$

$$\overline{u'(t)} = 0 \qquad (6.3)$$

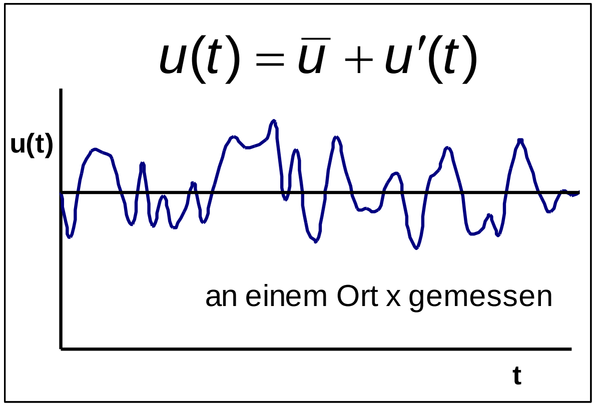
$$u' \equiv u'_{rms} = \sqrt{\overline{\left(u'(t)\right)^2}} \qquad (6.2)$$

"Turbulence intensity" ***(Fluctuation velocity = Root-Mean-Square Velocity)***

"Turbulence degree" (v. Kármán Number)

$$Tu \equiv \frac{u'}{\bar{u}} \qquad (6.4)$$

(typ. *Tu* < 10% for grid turbulence)

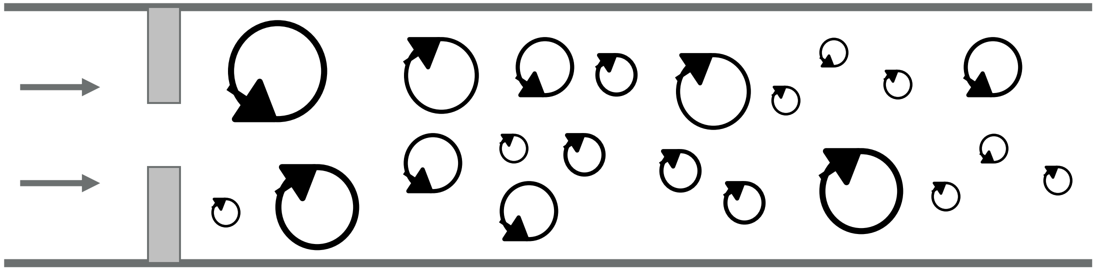


Turbulence quantities

Concept of Eddy cascade

Eddies of different size

"Concept of eddy cascade" (eddy spectrum)



Hindrance -> Large eddies -> smaller eddies -> very small eddies

(Energy transport = Dissipation rate ε)

-> Molecular dissipation (to heat)

"Integral length scale" L_x
("Macro length scale")

***"Kolmogorov-scale" η** (or l_k)*
("Micro length scale")

Turbulence quantities

Transition laminar - turbulent

Reynolds number

$$Re = \frac{\overline{u} \cdot D}{\nu} \qquad (6.5)$$

Note: depends on geometry !
D = geometrical size
ν = kin. viscosity

$Re_{kr} \approx 2200$	Flow in tube
100 - 1000	Axial free jet flow

"Turbulent Reynolds number"

$$Re_t = \frac{u' \cdot L_x}{\nu} \qquad (6.6)$$

Independent from geometry !
characteristic local quantity

turbulent: $Re_t > 1$

Note: Re_t is about 100 - 1000 times smaller than Re

Turbulence quantities

Turbulence characterization:

(**Assumption**: fully developed turbulence, homogeneous, isotropic)

Turbulent fluctuation velocity	$u' = u_{rms}$	(measured)
Integral length scale (Macro length)	L_x	(measured)
Turbulent Reynolds number	$Re_t = u' L_x / \nu$	(6.7)
Kolmogorov length (Micro length)	$\eta = L_x / Re_t^{3/4}$	(6.8)

Increase of turbulent Reynolds number broadens turbulence spectrum

<u>Note aside:</u> in some articles the Taylor length is used:

Taylor length	$l_\lambda = 6{,}3\, L_x / Re_t^{1/2}$	(6.9)
Local mean turbulent strain rate (Scherrate)	$a = u' / l_\lambda$	(6.10)

6.2 Turbulent premixed Flames

Turbulent premixed flames

- Fuel and air are premixed
- Danger of flash back
- Lean premixed flames can have low pollutant emissions:
  - No soot
  - Very low NO_X formation (stationary gas turbines, 'Blue burner')
- Turbulence increases the density of reaction ($P_{thermal}$ / V_{flame}). How ?

6.2.1 Structure of turbulent premixed flames

6.2.2 The Borghi diagram

6.2.3 Turbulent flame speed

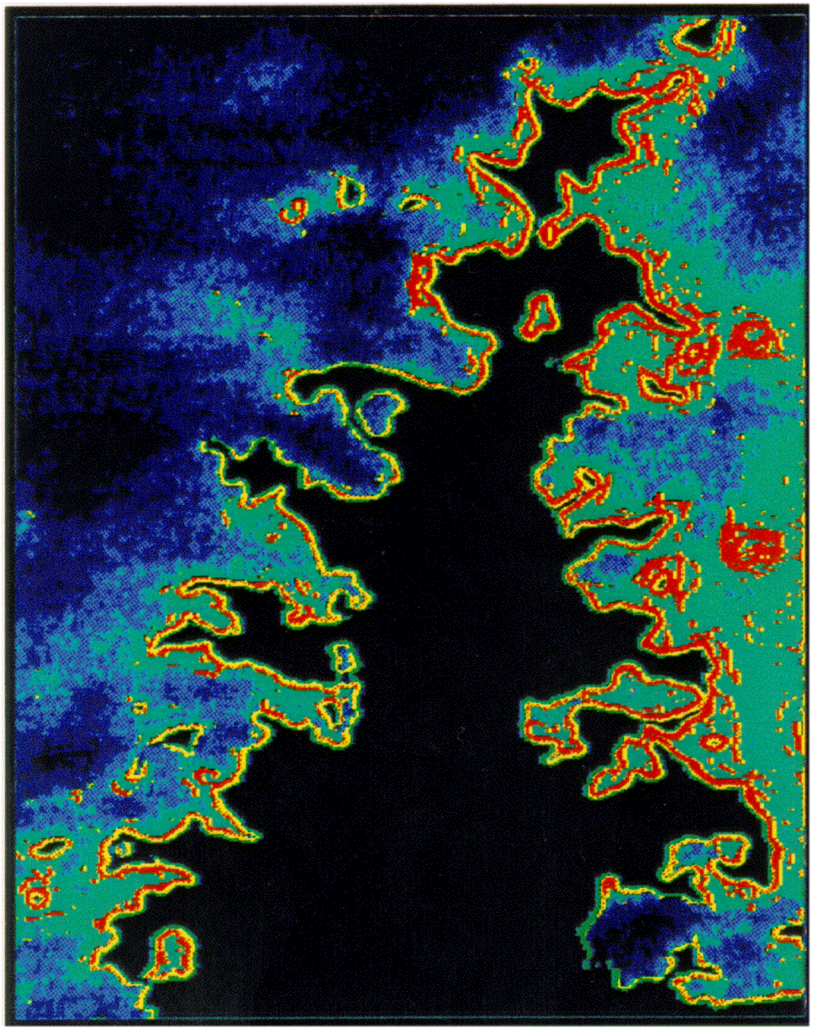
6.2.4 Flamelet model for calculation of turbulent premixed flames

Turbulent premixed flames

Bunsen
flame
(Heidelberg)

D=80 mm
100 kW

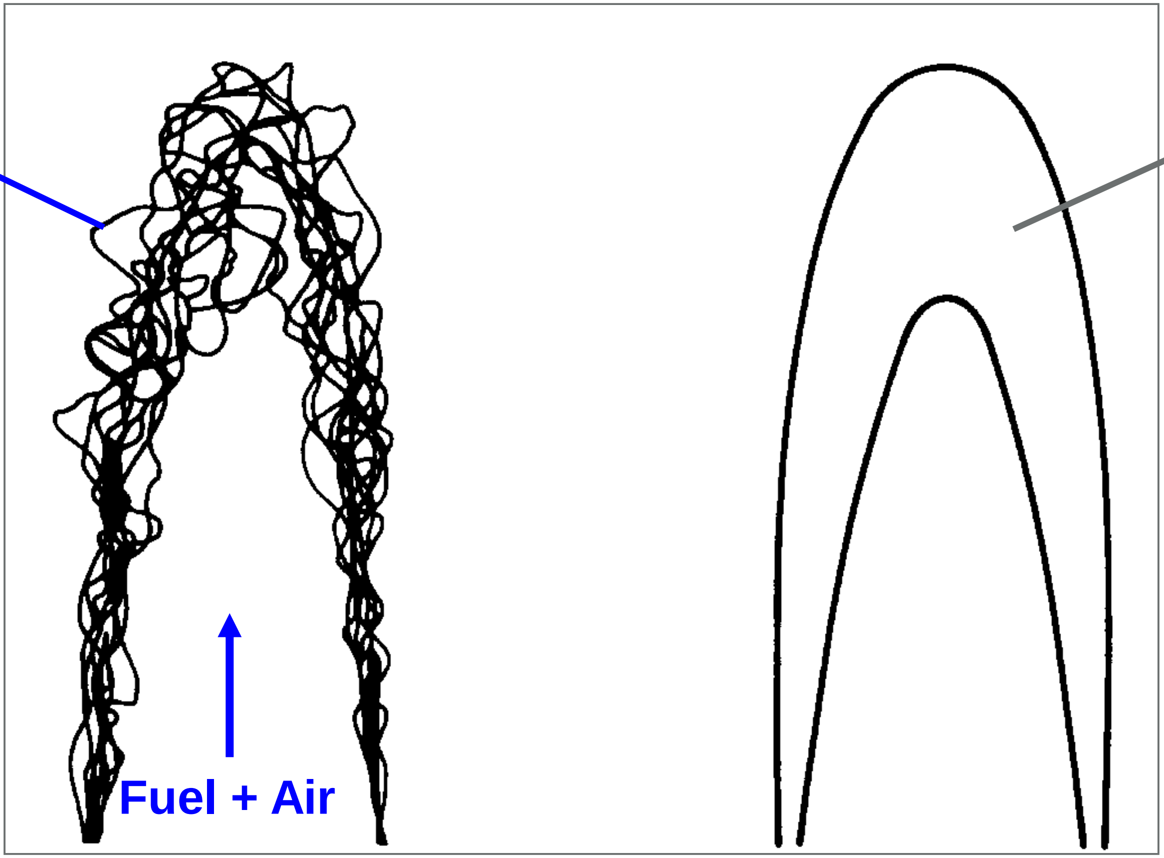
Photograph:
Laser-
diagnostics
(15x10 cm)



Turbulent premixed flames

Several instantaneous images

Average image



Flame front

(Flammenfront)

Flame brush

(Flammen-zone)

Fuel + Air

Turbulence - Flame Interaction

→ **Turbulent flow field has strong influence on premixed flames**

- Details of turbulence-flame interaction only barely known for long time.
- Theoretical analysis:

→ **Regime diagram following Borghi and Peters**

- Experimental verification was difficult for long time
  - Flame front fluctuates fast
  - Spatial flame structure < 1mm

Turbulent premixed flames

Borghi diagram *(Borghi 1985, Peters 1986)*

Two Turbulence quantities: *u', L_x*

Scaled with two laminar flame quantities s_L, δ_L

Log. Scales

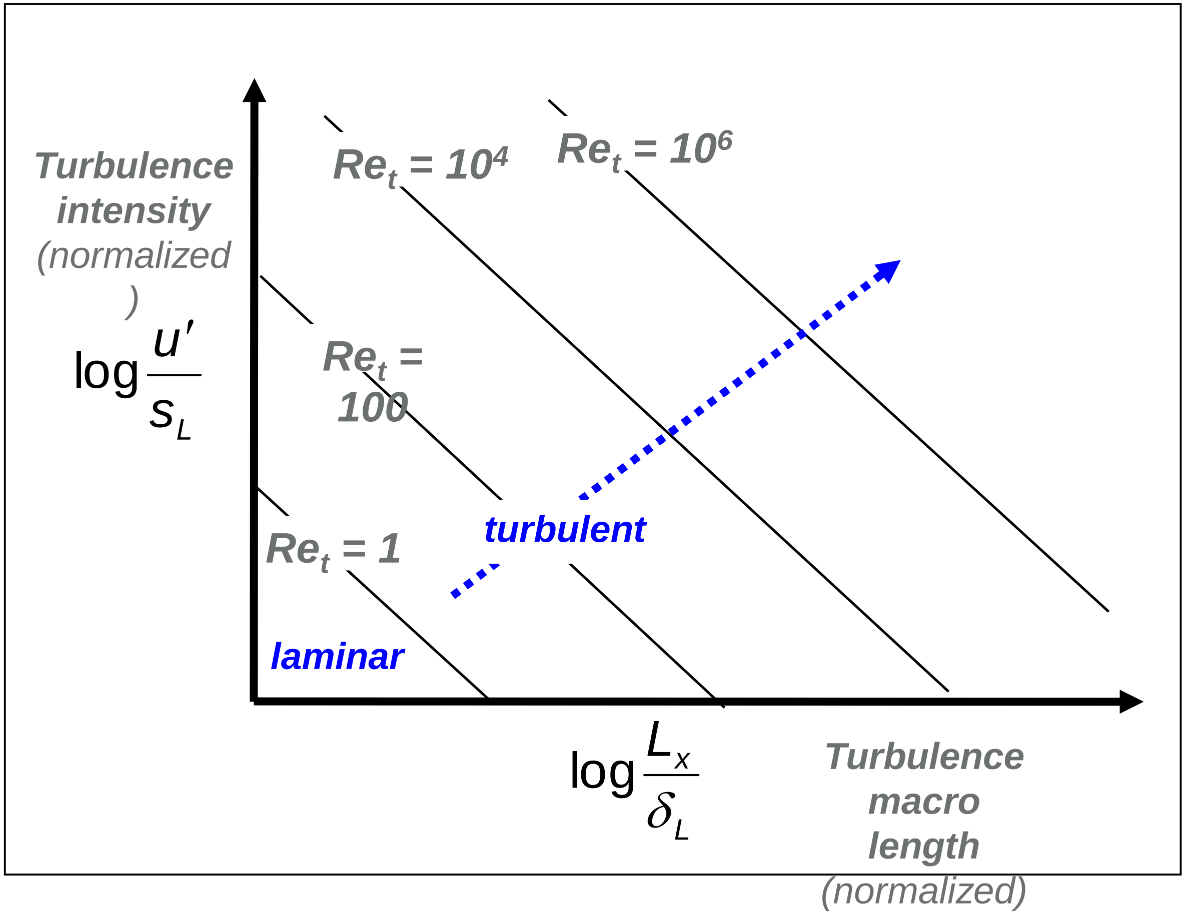
$Re_t = u' L_x / \nu$

indicates transition:
laminar - turbulent
and intensity of turbulence

Assumption: Le = a/D = 1

and Sc = ν/D = 1

hence: $\nu \approx a = s_L \cdot \delta_L^{Zeld}$



Turbulent premixed flames

Time Scales

Turbulent Regime:

Two extreme Cases:

mixing time << reaction time

"Stirred reactor"

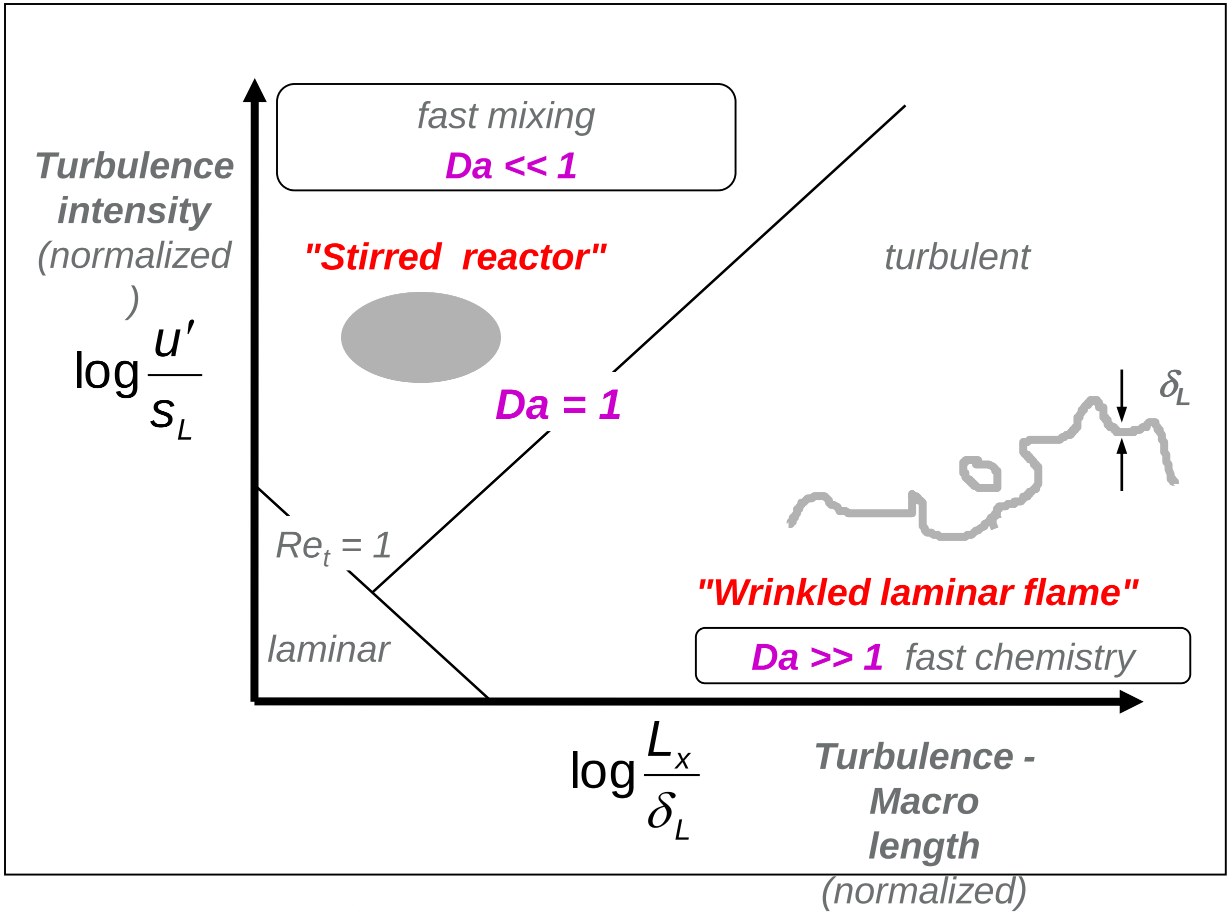
Da <<1

reaction time << mixing time

"Wrinkled laminar flame"

(however in a turbulent flow)

Da >>1



Damköhler number

$$Da = \frac{\tau_{turb}}{\tau_{reak}} = \frac{L_x / u'}{\delta_L / s_L} \qquad (6.11)$$

(Turn over time of large eddy)

(Transit time through lam. flame)

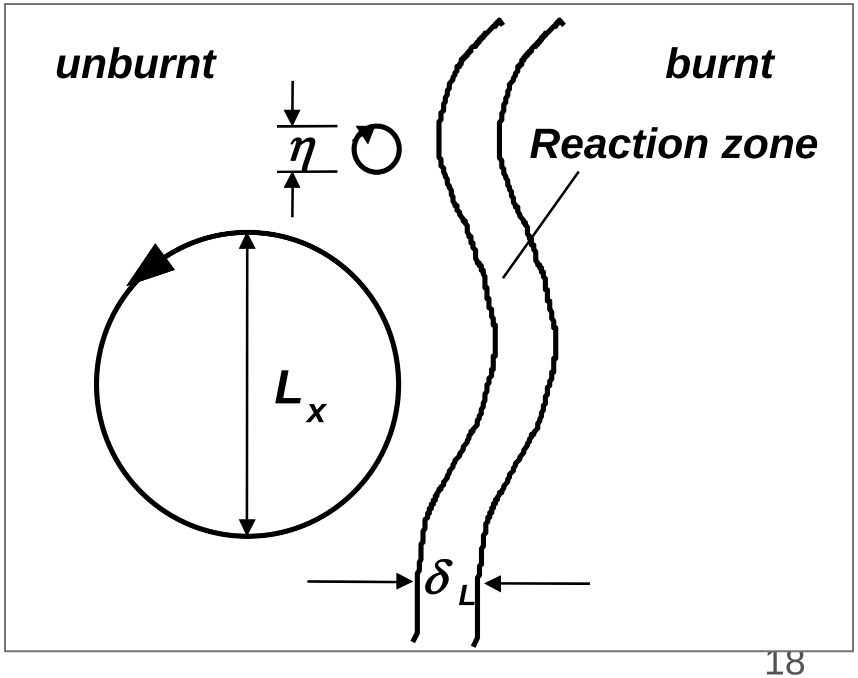
Turbulent premixed flames

Length Scales

Model:

Large Eddies ($l >> \delta_L$) -> wrinkle flame front

Small Eddies ($l << \delta_L$) -> enter the flame front, increase diffusive transport within the flame front -> **they thicken the flame front**



Comparison of length scales:

Karlovitz number:

$$Ka = (\delta_L / \eta)^2 \qquad (6.12)$$

with smallest "Kolmogorov-Eddies"

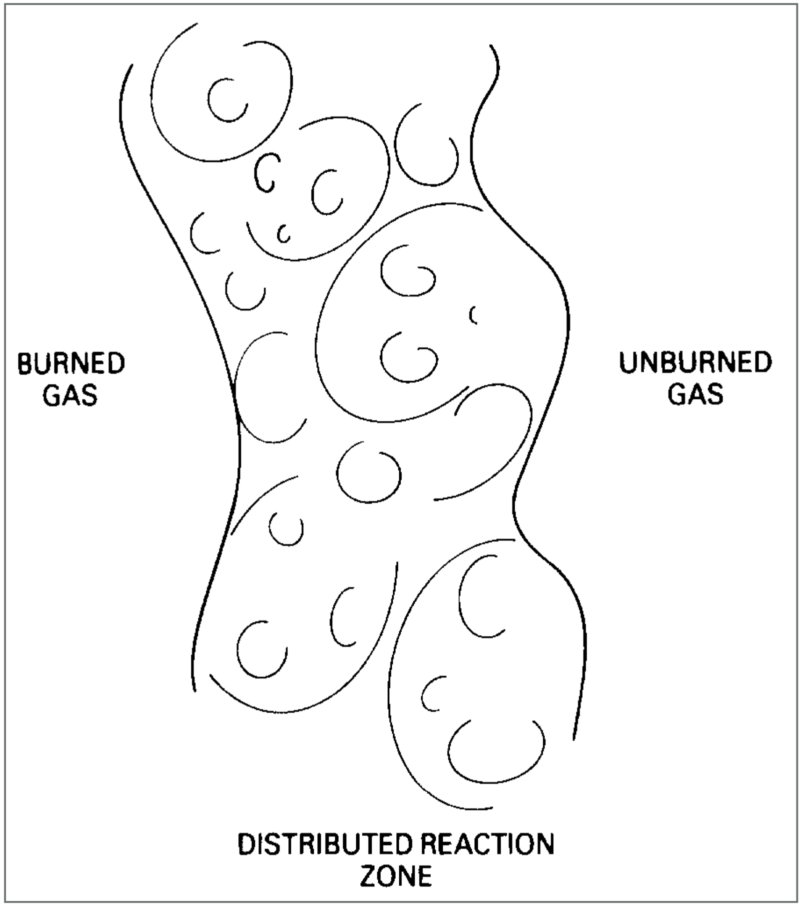
$$\eta = L_x / Re_t^{3/4}$$

Turbulent premixed flames

Distributed reaction zone

Model for the regime of distributed reaction zones

(foll. Turns)



Above which limit the smallest eddies enter the reaction zone ?

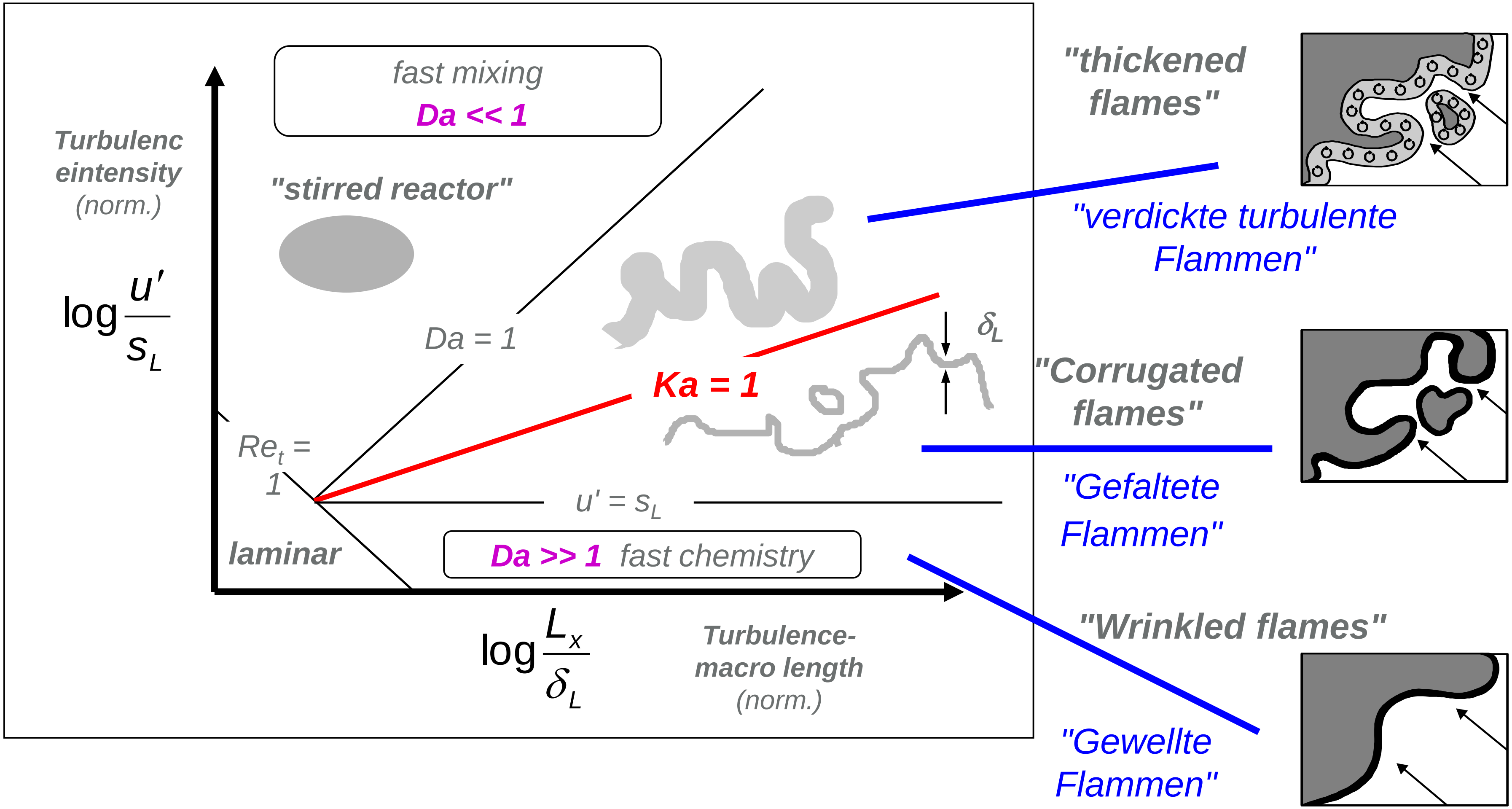
Supposition ("Klimov-Williams Criterion"):

Thickening, if $\eta < \delta_L$

$i.e.\ Ka > 1$ (6.13)

Turbulent premixed flames

Borghi diagram



fast mixing
Da << 1

Turbulenc eintensity (norm.)

$\log \frac{u'}{s_L}$

"stirred reactor"

Da = 1

Ka = 1

δ_L

$Re_t = 1$

$u' = s_L$

laminar

Da >> 1 fast chemistry

$\log \frac{L_x}{\delta_L}$

Turbulence-macro length (norm.)

"thickened flames"

"verdickte turbulente Flammen"

"Corrugated flames"

"Gefaltete Flammen"

"Wrinkled flames"

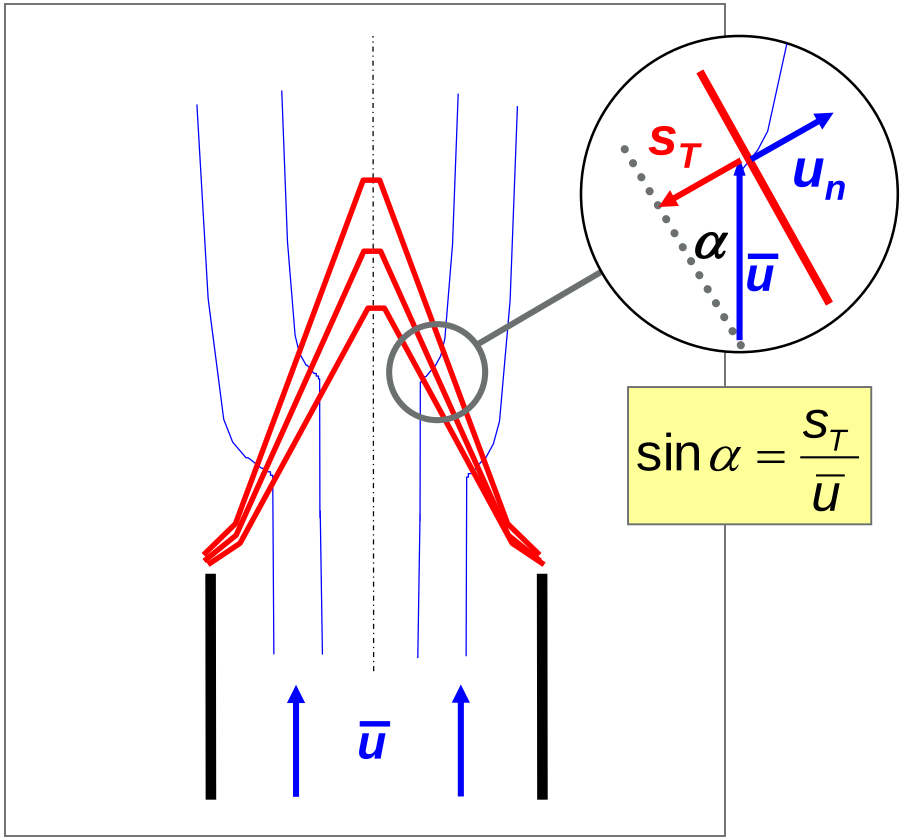
"Gewellte Flammen"

Turbulent premixed flames

Turbulent flame speed s_T

Definition: 'turbulent flame speed' s_T

Idea: Kinematic Balance between turbulent flame speed s_T and the normal velocity component u_n for stationary flames.



$$\sin\alpha = \frac{s_T}{\bar{u}}$$

Turbulent premixed flames

Turbulent flame speed s_T

Height of flame

as approximation

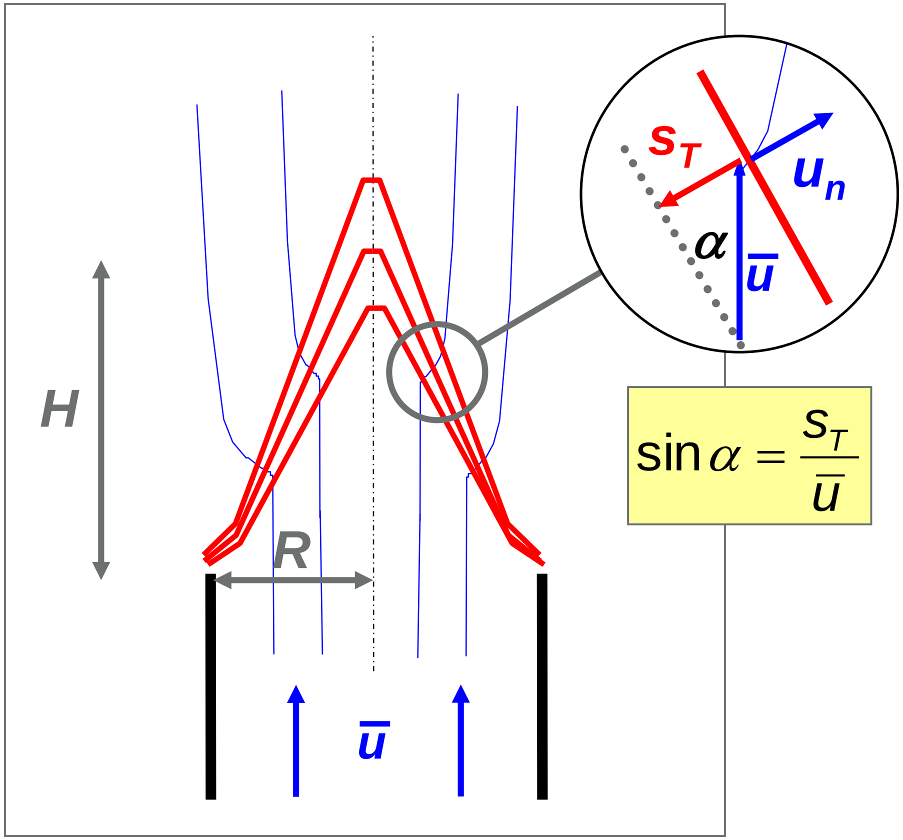
$$\sin\alpha = \frac{s_T}{\bar{u}} \qquad (6.14)$$

with unburnt gas velocity $\bar{u}$ and angle α between u and flame front.

For Bunsen flame (assumed u = const.) follows with

$$\tan\alpha = \frac{R}{H} \qquad (6.15)$$

as (rough) approximation the flame height *H.*



$$\sin\alpha = \frac{s_T}{\bar{u}}$$

Turbulent premixed flames

Turbulent flame speed s_T

Turbulent flame speed s_T is effective propagation velocity of premixed flame in turbulent flow field.

Necessary for calculation:

- Relation for s_T as function of
  - flame parameters (fuel, stoichiometry, p, T --> s_L)
  - Turbulence parameters (u', L_x, Re_t, Da, ...)

Is discussed in literature with several different approaches:

- **Theory (Damköhler 1940):** For wrinkled laminar flame surfaces the turbulent reaction rate and thus also the turbulent flame speed is proportional to geometrical flame surface area

$$\frac{s_T}{s_L} = \frac{A_L}{A_T} = 1 + \frac{u'}{s_L} \qquad (6.16)$$

Turbulent premixed flames

Turbulent flame speed s_T

Measurements of flame propagation in turbulent stirred ignition bomb experiments (Bradley et al.): **Correlation from Gülder** (1990)

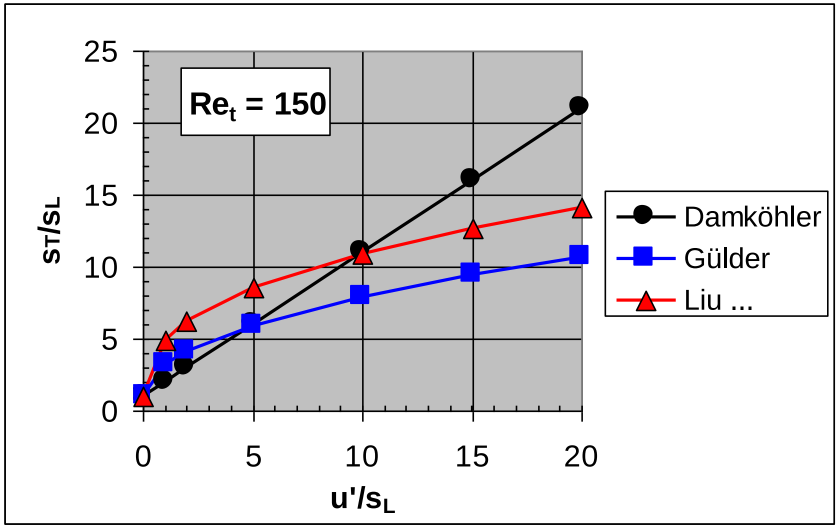
$$\frac{s_T}{s_L} = 1 + 0{,}62\left(\frac{u'}{s_L}\right)^{0{,}5} \cdot (Re_t)^{0{,}25} \qquad (6.17)$$

Measurement of normal component u_n directly before the flame front as function of turbulence and flame parameter **from Liu** et al. (1993)

$$\frac{s_T}{s_L} = 1 + 0{,}435\left(\frac{u'}{s_L}\right)^{0{,}4} \cdot (Re_t)^{0{,}44} \qquad (6.18)$$

Zimont (1995) (for $u' > s_L$), $A = 0{,}5 \ldots 1$

$$\frac{s_T}{s_L} = A \cdot Pr^{1/4} \cdot Re_t^{1/4} \cdot \left(\frac{u'}{s_L}\right)^{1/2} \qquad (6.19)$$



Turbulent premixed flames

Calculation of turbulent premixed flames

- Numerical calculation procedure for turbulent premixed flames is difficult
- Aim: Combustion model to be coupled to computational fluid dynamics (CFD)
- Not yet for practical applications, current research topic
- Possible approach:

  Borghi diagram shows:

  Typical: Wrinkled thin flame fronts, locally similar to laminar, if $Ka < 1$

  (Measurement (--> LTT) shows, even if $Ka < 10 \dots 100$)

  then ...

Turbulent premixed flames

“Flamelet“ –Approach: *Peters 1986*

For laminar-like wrinkled flame fronts a decoupling is possible between turbulence and reaction :

- Turbulent flow field wrinkles the flame
- Reaction remains similar as in laminar case (maybe modified from curvature or strain effects)

Flamelet-approach simplifies numerical calculation significantly !

Calculate basically the place of reaction (averaged), while the detailed chemistry is known from laminar flames.

Turbulent premixed flames

“Flamelet“ –Approach

for that introduce a mean reaction progress variable $\bar{c}$

$$\bar{c} = \text{Probability to find burnt gas} \left(\text{remember}: \; c = \frac{T - T_0}{T_{\max} - T_0} \right)$$

For this variable basically one balance equation is enough instead of *N* equations for energy and species.

This equation can be calculated numerically together with the flow field (+ turbulence model).

Several approaches for this *c*-equation (sometimes also called *G*- or Σ-equation) are discussed in the literature

One approach, based on turbulent flame speed, gives e.g.
(Dinkelacker, Helbig, Hölzler 1999): (next page)

Turbulent premixed flames

Example for Flamelet-Model **Turbulent-Flame-Speed-Closure (TFC)**

Idea:

- Average reaction rate ~Turbulent flame speed
- This yields a "Turbulent-Flame-Speed-Closure" for averaged reaction term (Zimont & Lipatnikov 1995)

$$\overline{w}_c = \rho_u \; \hat{s}_T(x) \cdot \left|\nabla \overline{c}\right| \tag{6.21}$$

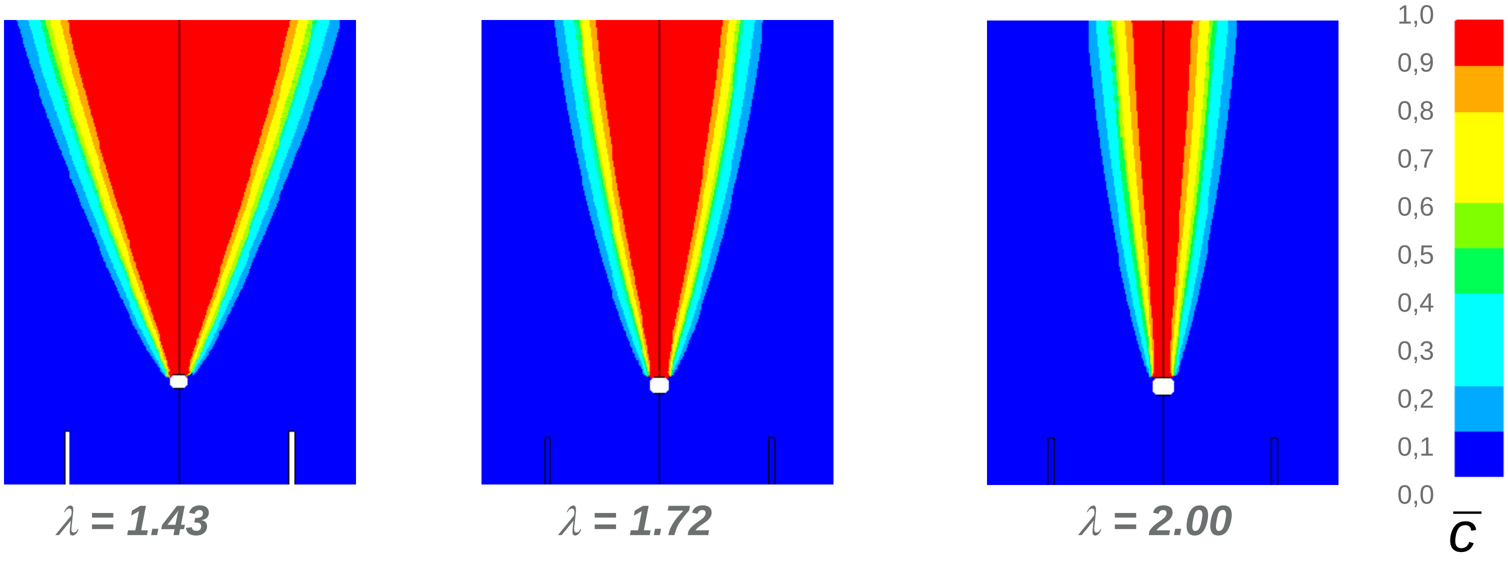
place of reaction

- Turbulent burning velocity, e.g., from equation (6.19), for application with pre-factor of *A* = 0,52 (Zimont & Lipatnikov 1995)
- Solution as subroutine with standard-CFD-program (e.g.,Fluent)

Turbulent premixed flames

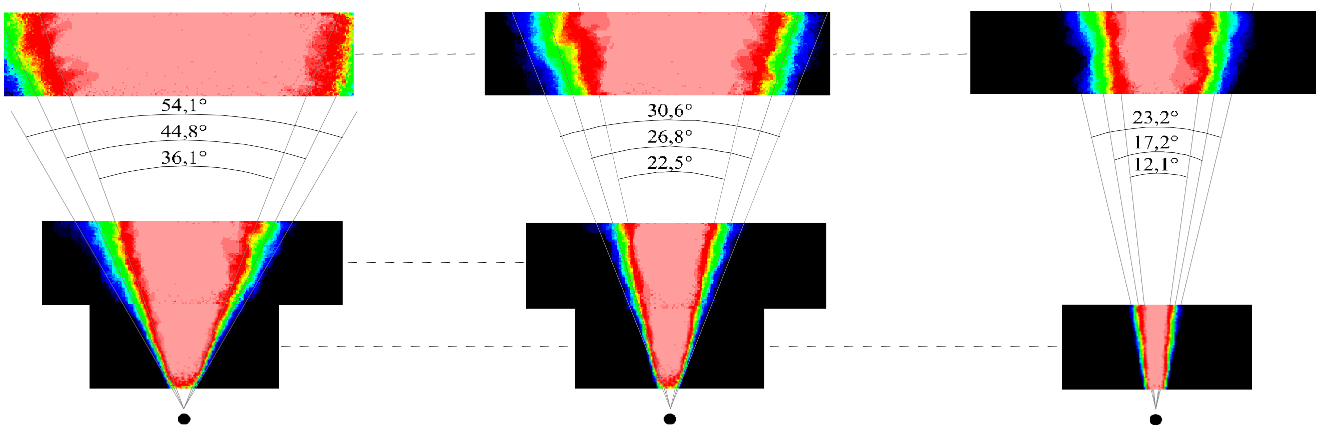
Testcase: turbulent premixed V-flame: Reaction progress c̄

Simulation



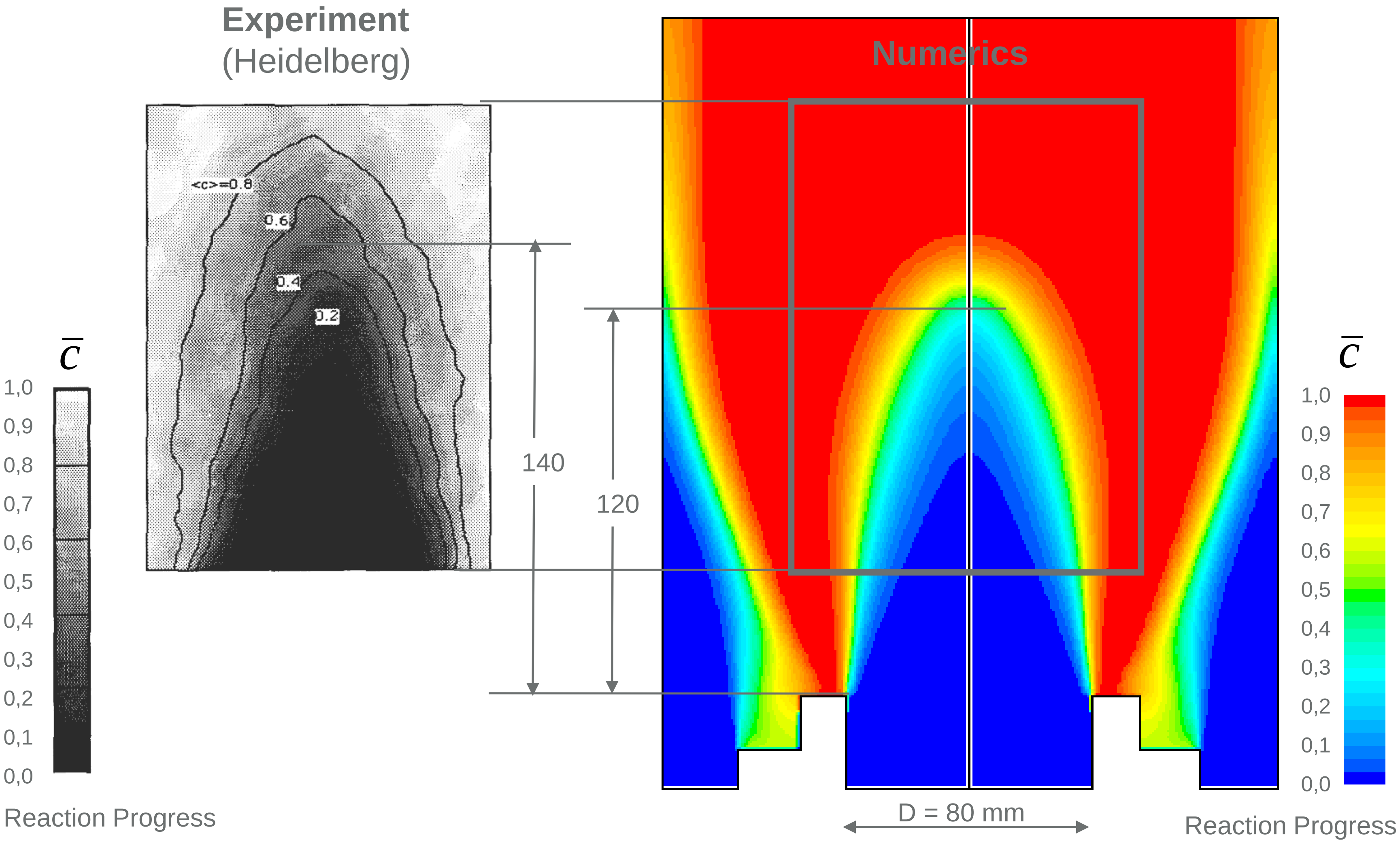
Experiment

2-dim. Rayleigh-Thermometry (A. Soika)



Turbulent premixed flames

Testcase: 80 mm - Bunsen Flame



Experiment
(Heidelberg)

Numerics

(F. Dinkelacker, R. Muppala, SIAM 2002)

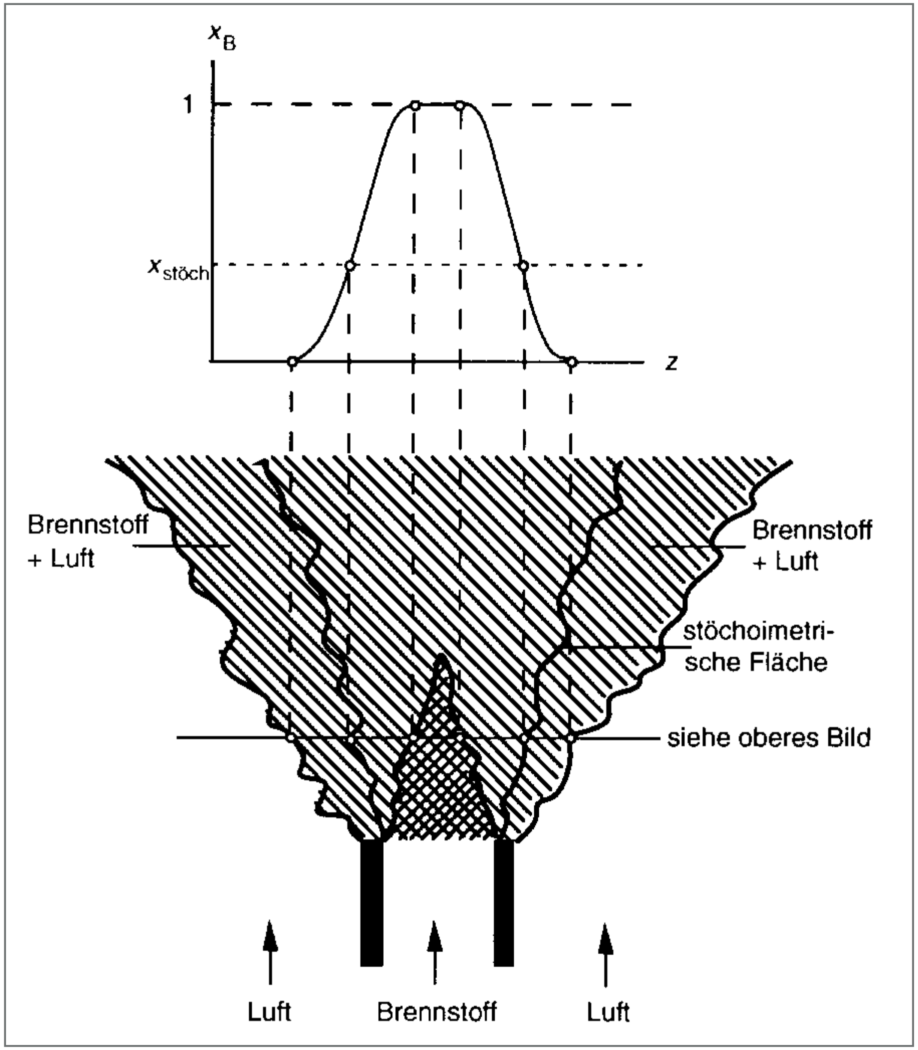
Turbulent non-premixed flames

6.3 Turbulent non-premixed flames

- Fuel and air are mixed in burning chamber
- Turbulence supports mixing
- Large practical relevance
- Also for solid and liquid fuels
- Disadvantage: More pollutants and soot as premixed flames

3.1 Examples
3.2 Flame length
3.3 Mixture fraction-concept

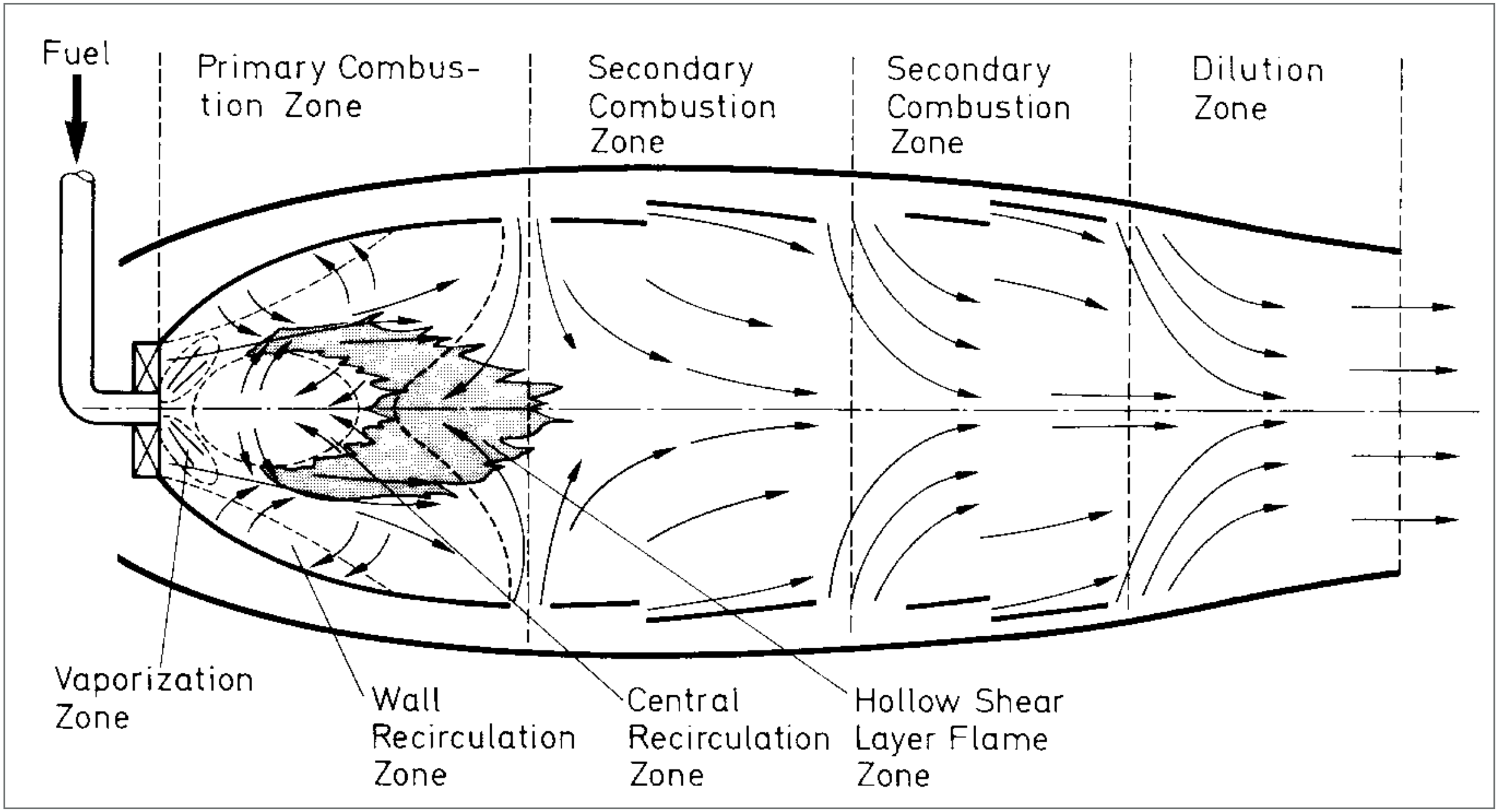
Turbulent non-premixed flames



Snap-shot of a turbulent jet-diffusion flame (schematics)

Turbulent non-premixed flames

Example: Burning chamber of air gas turbine (schematic)



Use of non-premixed (diffusion) flames owing to safety reasons (flashback)

Turbulent non-premixed flames

Mixture fraction concept

Numerical calculation of diffusion flame

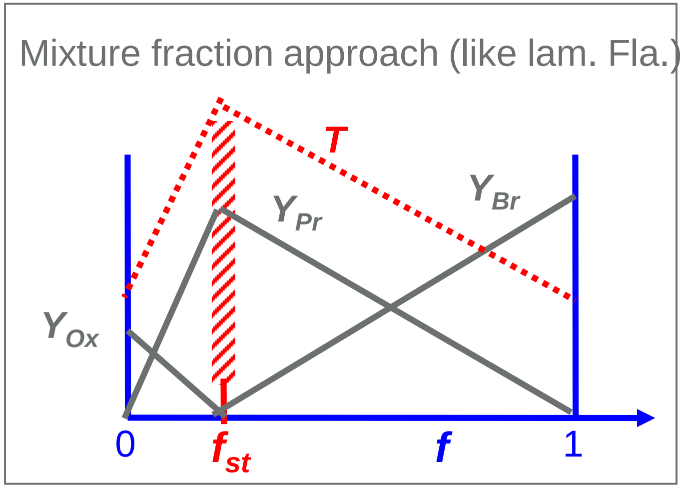
Aim: Numerical calculation of flame location and flame length.

Models for diffusion flames often are based on observation, that mixing controls the reaction. Then the flow field couples with mixture fraction *f* ; to be calculated instead of species and temperature:

- Flow field, averaged $(\bar{u}_i, \bar{p})$
- Turbulence field (k, ε)
- Mixture fraction field $(\bar{f}, f')$

Allocation only once (ideal situation, see ->)

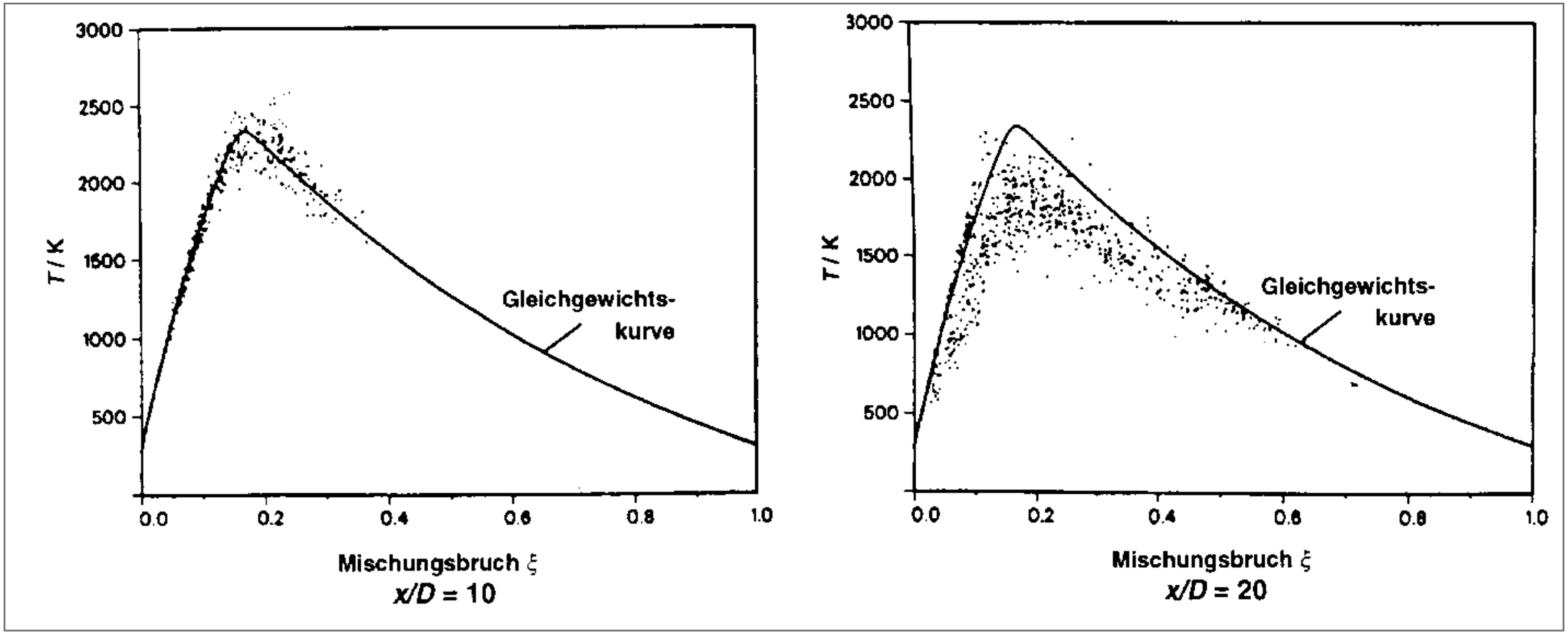
- $\bar{f}, f' \rightarrow$ Temperature field
  $\rightarrow$ Heat release
  $\rightarrow$ Species distribution



Mixture fraction approach (like lam. Fla.)

Turbulent non-premixed flames

Mixture fraction concept



Temperature as function of mixture fraction

Turbulent non-premixed hydrogen jet flame, left: low turbulence, right: higher turbulence intensity

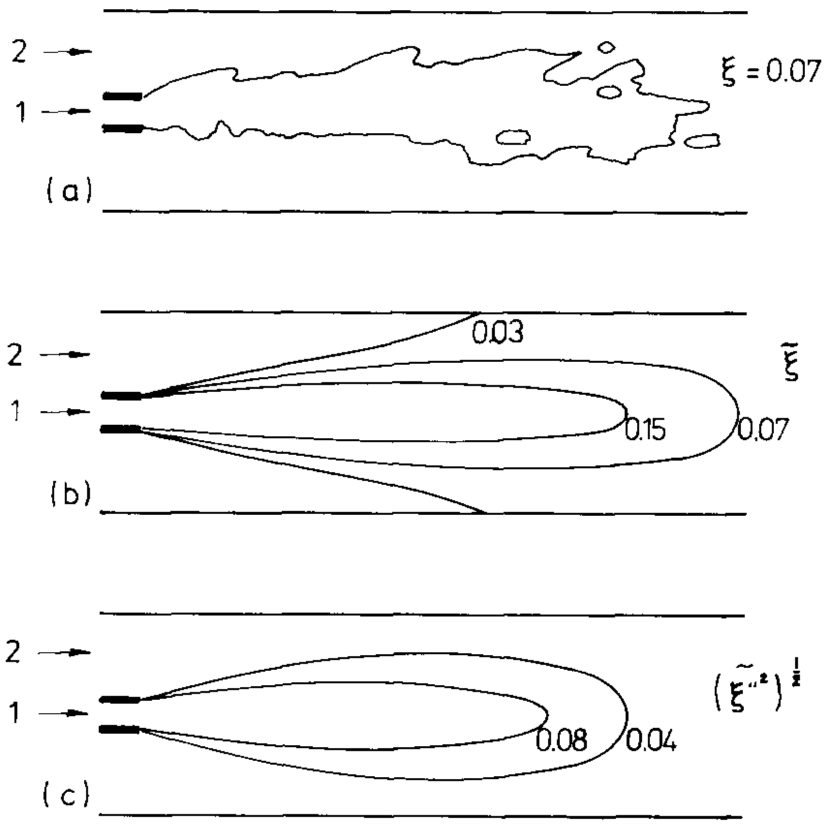
Measured (Laser-Raman-Scattering) vs. equilibrium calculation

(Magre, Dibble 1988, cit. after Warnatz et. al. 96)

Turbulent non-premixed flames

Mixture fraction concept

Example: Mixing field of a typical non-premixed turbulent flame



Mixture fraction, instantaneous distribution (iso-line for *f* = 0,07)

Mixture fraction, mean value

Mixture fraction, average fluctuations

f. Bilger

Summary

Turbulent combustion to enhance mixing

- Turbulence-Flame Interaction
- Two extreme cases allow 'separation' of turbulence and reaction:
  - 'Fast mixing limit' (Stirred reactor model):
    spatially homogeneous chem. reactions
  - 'Fast chemistry limit': Wrinkled laminar 'flamelet'
    'flamelet' - approach

Turbulent premixed flames

- Typically: fluctuating wrinkled thin flame **fronts** result in a broad flame **brush**
- Turbulent flame speed s_T
- **Flamelet models** for calculation

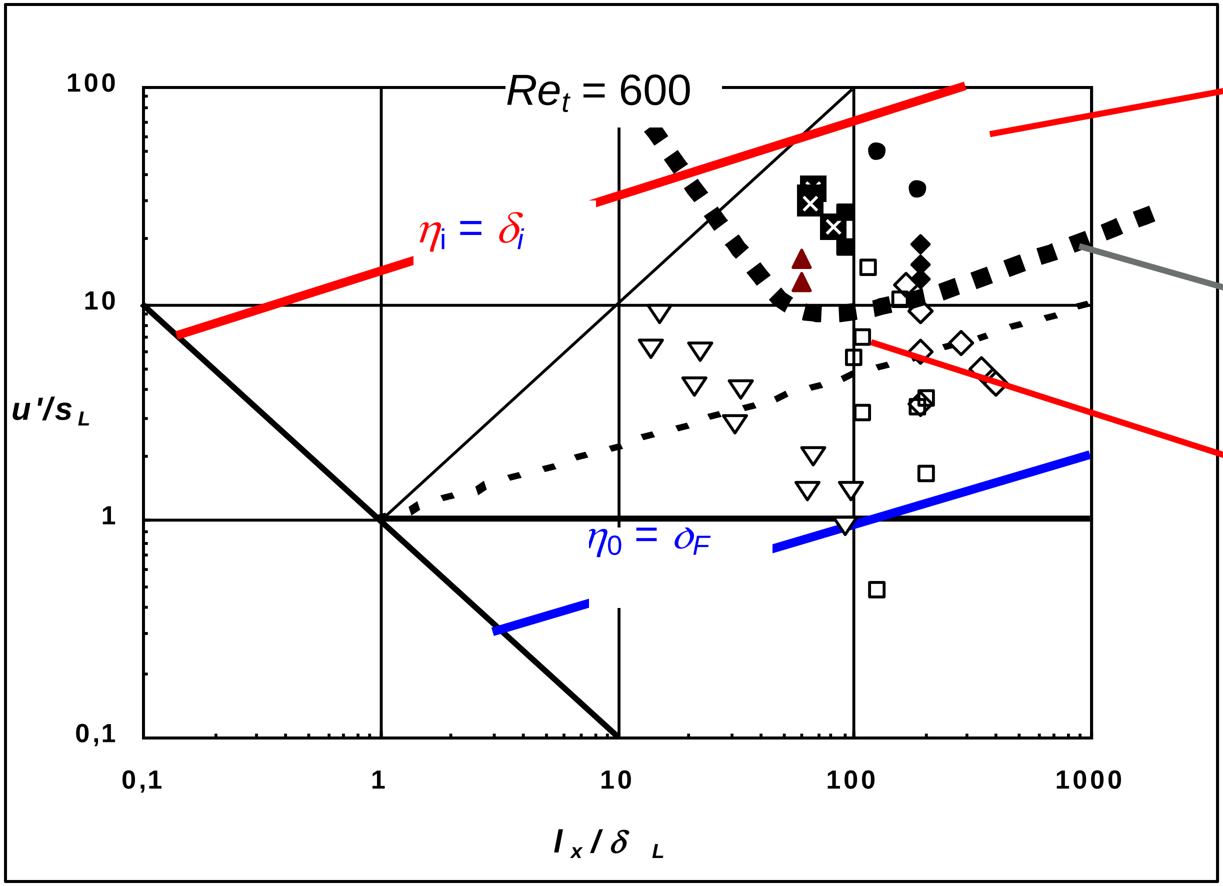
Turbulent diffusion flames

- Turbulence enhances fuel-air mixing
- Mixture fraction concept

Turbulent premixed flames

Results of experiment of premixed turbulent flame structure

Range of wrinkled laminar-like flames (Flamelet) is more extended



Thin reactions zone, Locally modified preheat zone

$\delta_V = 8\ \eta_{kalt}$

No significant thickening
(partly even thinned flames instead *)

Details, see *

* Dinkelacker, 20. Deutscher Flammentag, VDI-Berichte Nr. 1629, S. 473 (2001)

Turbulent premixed flames

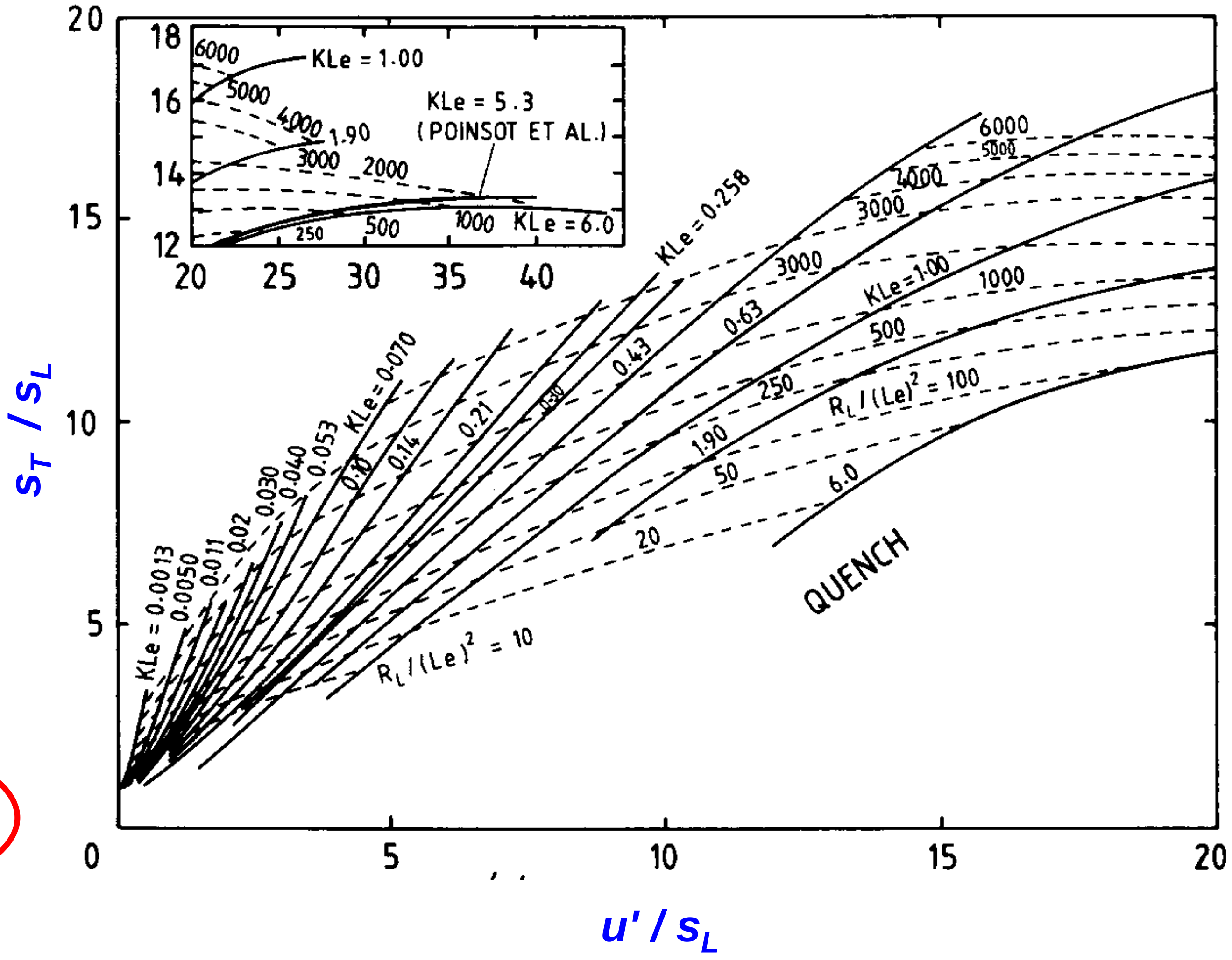
Turbulent flame speed s_T

foll. Bradley,
24. Comb. Symp. (92):

R_L = turb. Reynolds number
Le = Lewis number
K = dimensionless
Strain rate

$$K = \left(\frac{a}{s_L / \delta_L} \right) = \left(\frac{u'/\lambda}{s_L / \delta_L} \right)$$

Critics:
Measured flames
have been very small



Turbulent premixed flames

Turbulent flame speed s_T

For increasing turbulence (*u'/s_L*) the turbulent flame speed increases slower (*"Bending Effect"*).

Possible reasons:

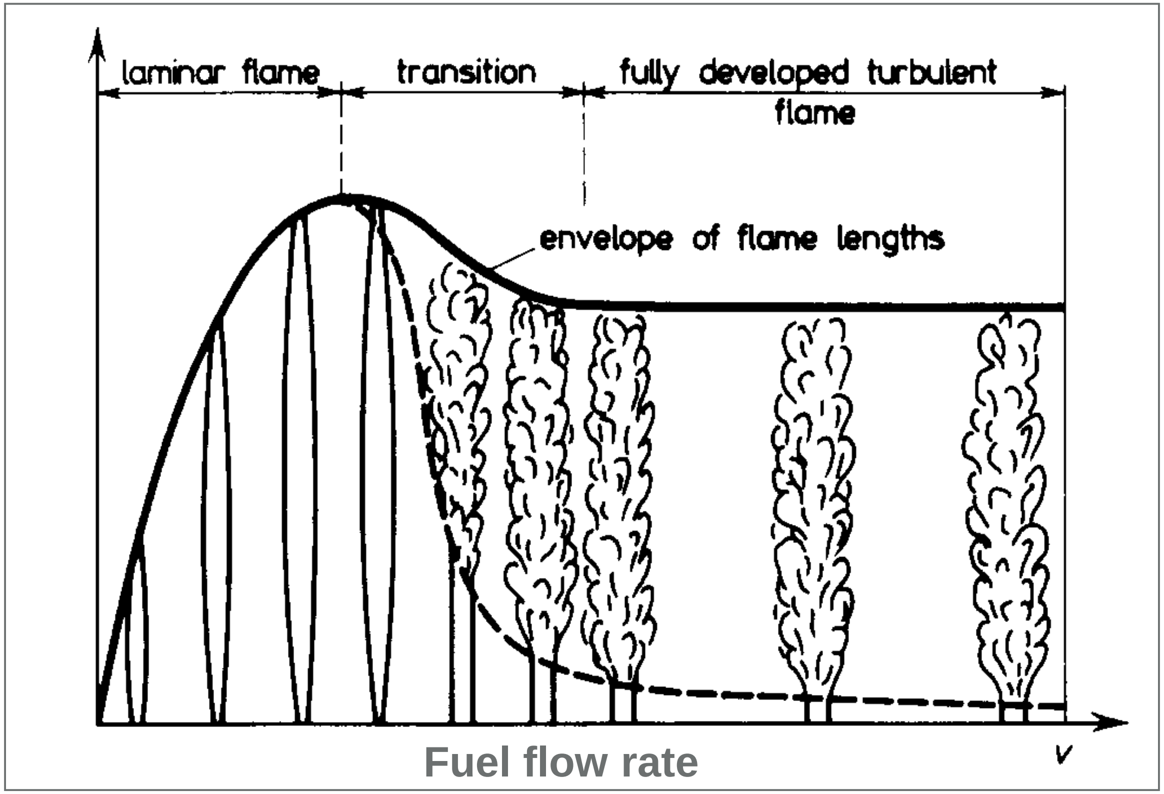
- Flame area increases not with u'/s_L, but annihilates due to interaction
- Reaction locally reduced compared with "laminar flamelets", due to
    - local curvature
    - Influence of small scale eddies
    - local breaks in reaction front (flame quench) ?

For further increase of *u'/s_L* flame quenches totally.

Turbulent non-premixed flames

Length of turbulent jet non-premixed flames

Length of flame nearly independent on fuel exit velocity, for developed turbulent flame



Turbulent non-premixed flames

Length of turbulent jet non-premixed flames

Empirical relation for flame length of turbulent jet non-premixed flame
(Delichatsios 93, Turns 96)
Length of diffusion flame is controlled by mixing. From that the following relation is derived for jet flames (here for "sufficiently" large momentum of the fuel flow, buoyancy is neglected, calm surroundings; for other conditions see Turns 96).

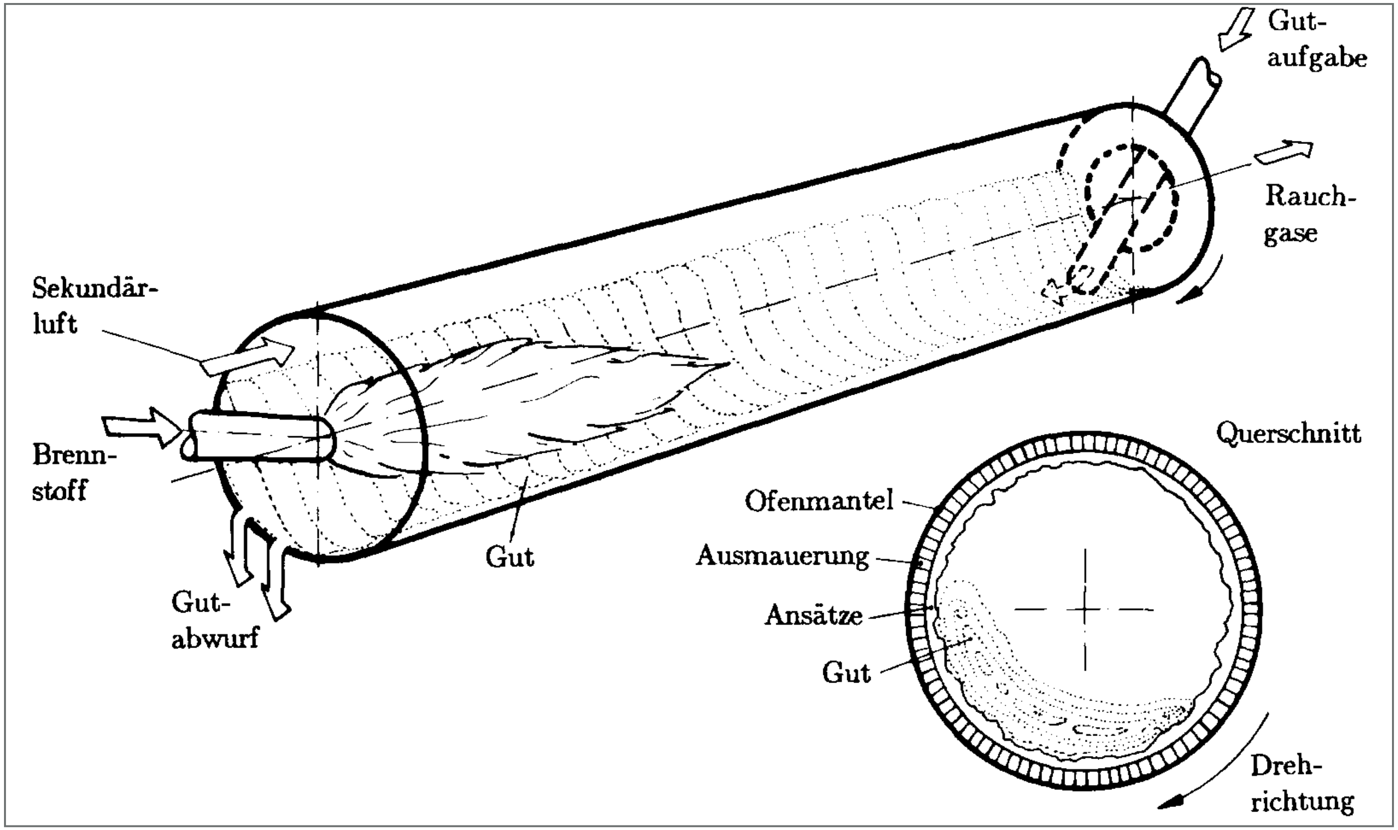
$$L_f = \frac{23 \cdot d_j \cdot \left(\rho_B / \rho_L \right)^{1/2}}{Y_{B,st}} \qquad (6.20)$$

Flame length L_f
Diameter of fuel inlet d_j
Density ratio between fuel and air ρ_B/ρ_L
Stoichiometric fuel mass fraction $Y_{\mathrm{B,st}}$ (Lecture 2, Table 2.1)

Note:
Length of flame is (approx.) independent of inlet velocity !
Length of flame is proportional to diameter of inlet!
Length of flame depends on fuel
Example: Methane in air, d_j = 10 mm, gives length L_f = 3,1 m

Turbulent non-premixed flames

Example: rotary furnace



Turbulent diffusion flame in rotary furnace for production of cement

(n. Görner)

(**Assumption**: fully developed turbulence, homogeneous, isotropic)

Turbulent fluctuation velocity	$u' = u_{rms}$	(measured)
Integral length scale (Macro length)	L_x	(measured)
Turbulent Reynolds number	$Re_t = u' L_x / \nu$	(6.7)
Kolmogorov length (Micro length)	$\eta = L_x / Re_t^{3/4}$	(6.8)

Increase of turbulent Reynolds number broadens turbulence spectrum