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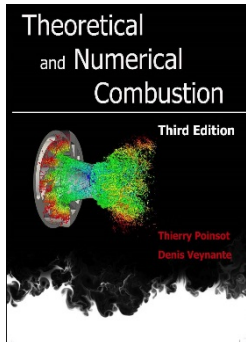
Iran First International Combustion School (ICS2019)
Tehran, 24-26 August 2019

Combustion Modeling

6. Turbulent Combustion Modeling

Alberto Cuoci

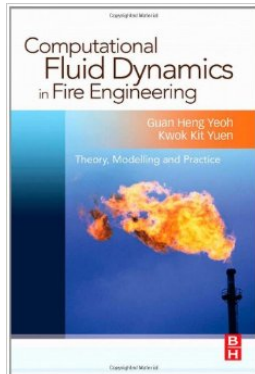
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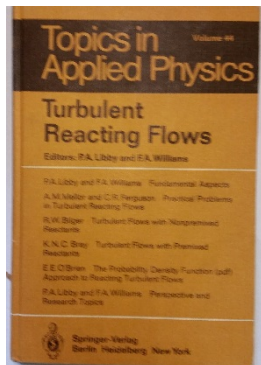
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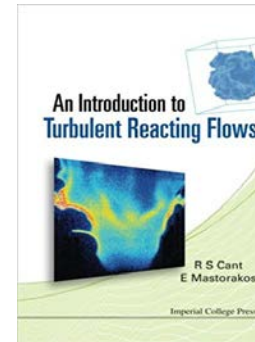
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Princeton Combustion Summer School 2018

<https://cefr.princeton.edu/combustion-summer-school/archived-programs/2018-session/lecture-notes>

1. Introduction to turbulent combustion modeling

- a) Fluid dynamic and chemical time scales
- b) Effects of turbulent fluctuations on chemical reactions
- c) Need of turbulent combustion models

2. Non-premixed combustion

- a) Eddy Dissipation models: ED, ED-FR, EDC
- b) Steady Laminar Flamelet model
 - i. Mixture fraction
 - ii. Flamelet equations
 - iii. Presumed PDF approach

3. Premixed combustion

- a) Eddy Break-Up (EBU) model
- b) Bray-Libby-Moss (BLM) model
- c) G-Equation

Introduction



Numerical modeling of turbulent combustion

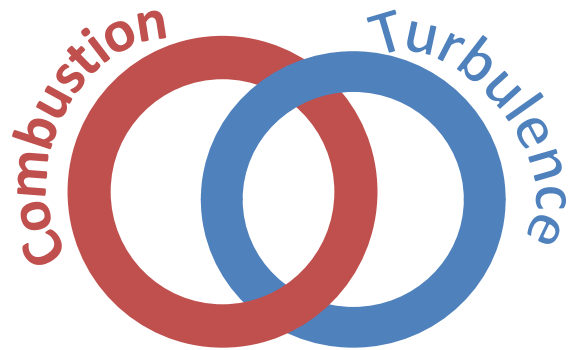
Complex numerical techniques
Computational resources

Large gradients of temperature
and composition
Wide range of characteristic
times (fluid dynamics and
chemistry)

Detailed kinetic mechanisms

- hundreds of species
- thousands of reactions

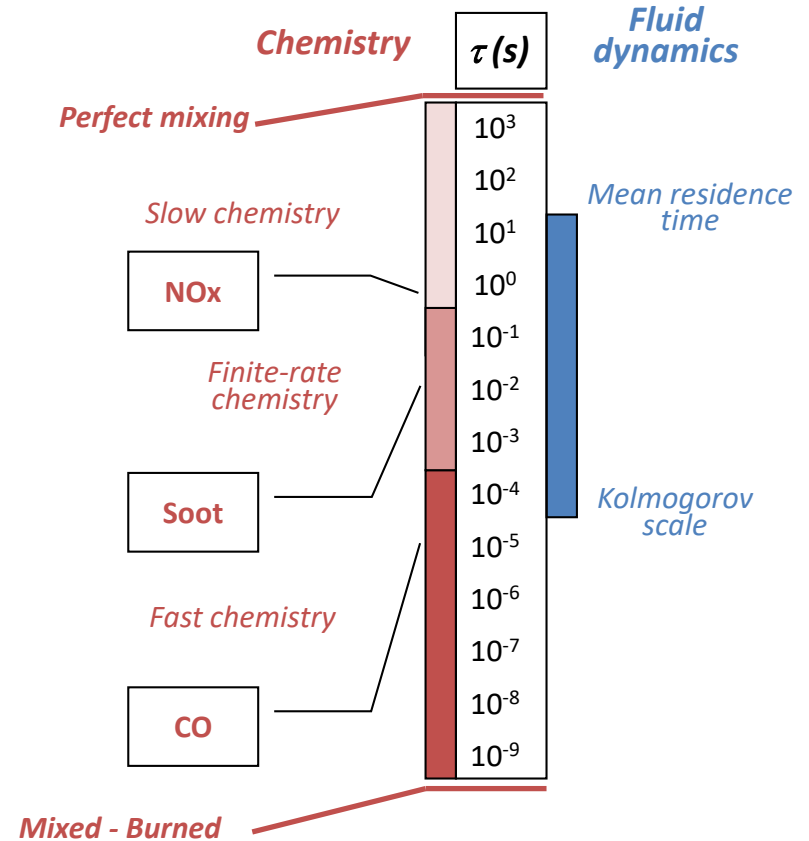
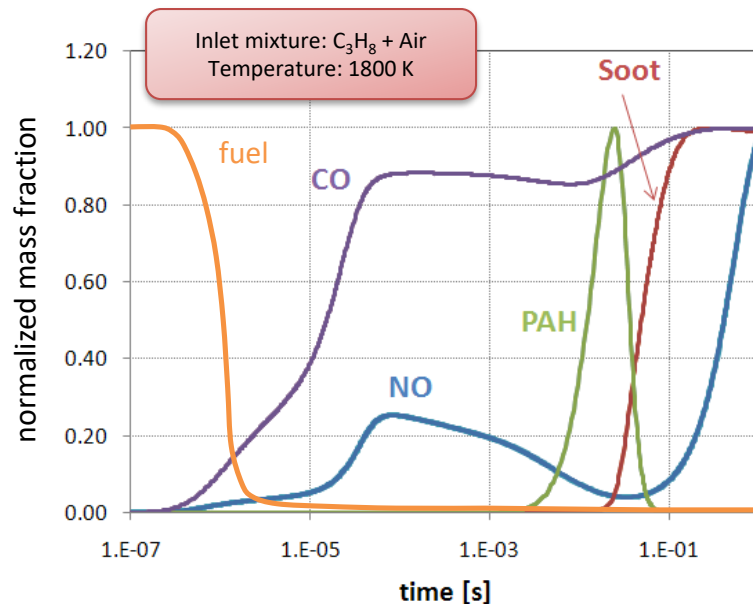
Turbulence-Chemistry Coupling



Combustion releases heat, strongly affecting the density of the mixture and therefore the fluid dynamics of the system



Turbulence can improve the mixing between fuel and oxidizer. However, if too large, extinction can occur



Adapted from Fox R.O., "Computational Models for Turbulent Reacting Flows", Cambridge, 2003

Characteristic times of chemistry

How to estimate the chemical characteristic times in a system with NS species and NR chemical reactions?

$$r_j = k_j \prod_{i=1}^{NS} C_i^{\eta_i^j} \quad j = 1, \dots, NR$$

Reaction rates

$$\dot{\Omega}_i = \sum_{j=1}^{NR} \nu_i^j r_j \quad i = 1, \dots, NS$$

Formation rates

Fox R.O.,
“*Computational Models
for Turbulent Reacting
Flows*”, Cambridge
University Press, 2003

Eigenvalues of Jacobian

$$J_{ij} = \frac{\partial \dot{\Omega}_i}{\partial C_j} \quad i, j = 1, \dots, NS$$

Jacobian matrix (based on
formation rates)

$$\tau_i = \frac{1}{|\lambda_i|} \quad i = 1, \dots, NS$$

Chemical characteristic times

Chemical vs Fluid dynamic control

Dimensionless parameter to characterize the combustion: **Damköhler Number**

$$Da = \frac{\tau_{flow}}{\tau_{chem}}$$

The fluid dynamic time depends on the features of the system. Each species has a proper characteristic time, depending on the formation rate

Two asymptotic behaviors can be observed:

Chemical regime

$$Da \ll 1$$

Chemical reactions extremely slow. The system is under chemical control

Fluid dynamic regime

$$Da \gg 1$$

Chemical reactions extremely fast. The system is under fluid dynamic control

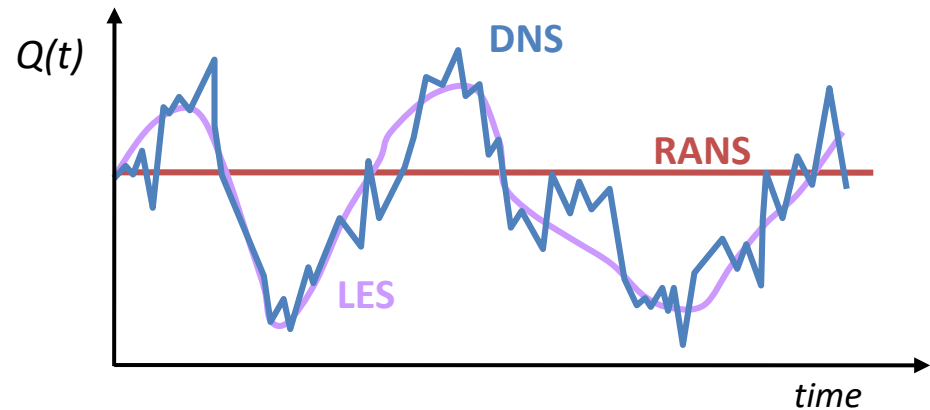
Peters N., "Turbulent Combustion", Cambridge University Press, 2000

Numerical modeling of turbulent reacting flows

DNS

Direct Numerical Simulation

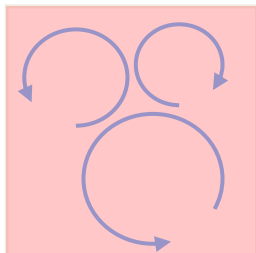
The equations of continuity, momentum, energy and species are solved directly without any manipulation. Extremely expensive from a computational point of view



LES

Large Eddy Simulation

The conservation equations are filtered and only the largest vortices are described. Vortices smaller than a characteristic length are only modeled.



RANS

Reynolds-Averaged Navier-Stokes

Only the mean variables are described.

Formation rates have to be modeled

$$\bar{\rho} \frac{\partial \widetilde{Y}_k}{\partial t} + \bar{\rho} \widetilde{u}_i \frac{\partial \widetilde{Y}_k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\overline{\rho D_k} \frac{\partial Y_k}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \left(\bar{\rho} \widetilde{u_i'' Y_k''} \right) + \bar{\rho} \widetilde{\dot{\Omega}_k}$$

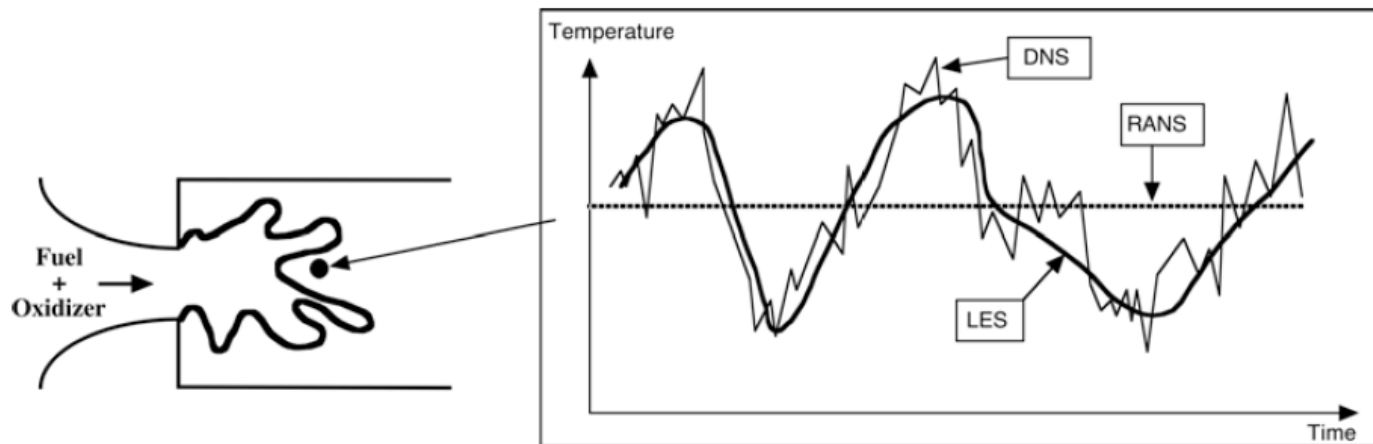
Reynolds Averaged Navier-Stokes (RANS)

- Reynolds Averaged Navier-Stokes (or RANS) computations have **historically** been the first possible approach because the computation of the instantaneous flow field in a turbulent flame was impossible.
- Therefore, RANS techniques were developed to solve for the **mean values** of all quantities.
- The **balance equations for Reynolds or Favre averaged quantities** are obtained by averaging the instantaneous balance equations.
- The averaged equations require **closure rules**: a **turbulence model** to deal with the flow dynamics in combination with a turbulent combustion model to describe chemical species conversion and heat release.
- Solving these equations provide averaged quantities corresponding to **averages over time** for stationary mean flows or **averages over different realizations** (or cycles) for periodic flows like those found in piston engines (i.e. phase averaging).
- For a stabilized flame, the temperature predicted with RANS at a given point is a constant corresponding to the mean temperature at this point.

Poinsot T., Veynante D., *"Theoretical and Numerical Combustion"*, R.T. Edwards, 2nd Edition, 2005

Large Eddy Simulation (LES)

- The turbulent large scales are explicitly calculated whereas the effects of smaller ones are modeled using subgrid closure rules.
- The balance equations for large eddy simulations are obtained by filtering the instantaneous balance equations.
- LES determine the instantaneous position of a “large scale” resolved flame front but a subgrid model is still required to take into account the effects of small turbulent scales on combustion.
- LES would capture the low-frequency variations of temperature.

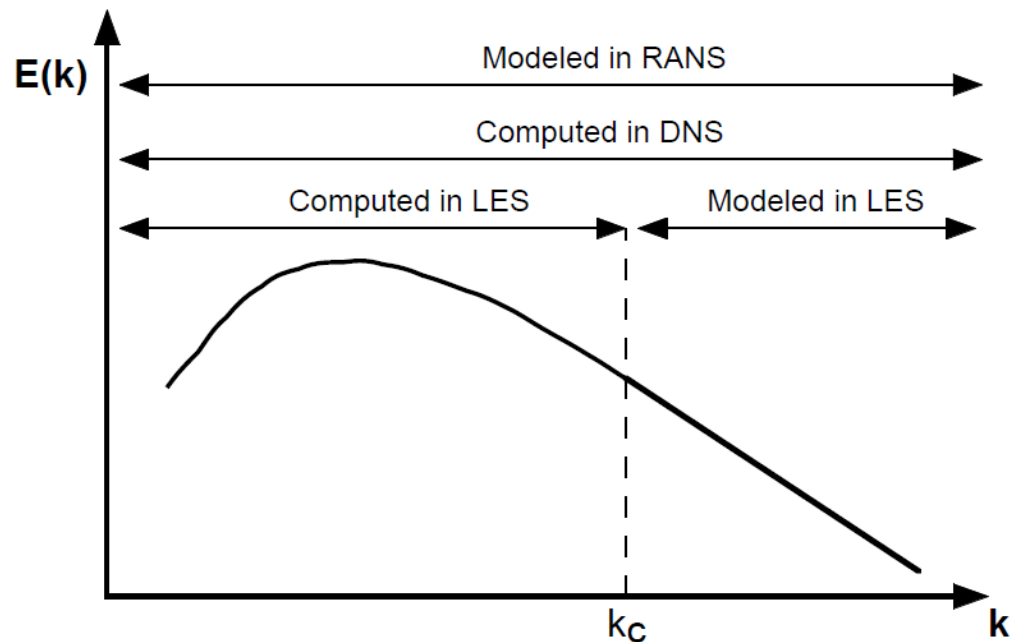


Poinsot T., Veynante D., “Theoretical and Numerical Combustion”, R.T. Edwards, 2nd Edition, 2005

Comparison: DNS, LES, and RANS

- All spatial frequencies in the spectrum are resolved in direct numerical simulations
- Only the largest ones (up to a cut-off wave number κ_c) are computed in LES (the effects of motions smaller than the cut-off length scale, having a wave number κ larger than κ_c , are modeled).
- In RANS, only mean flow fields are resolved: no turbulent motion is explicitly captured.

Turbulence energy spectrum plotted as a function of wave numbers. RANS, LES and DNS are summarized in terms of spatial frequency range. κ_c is the cut-off wave number used in LES (log-log diagram).



Poinsot T., Veynante D., "Theoretical and Numerical Combustion", R.T. Edwards, 2nd Edition, 2005

Computational requirements

- In terms of computational requirements, CFD for non-reacting and reacting flows follow similar trends: DNS is the most demanding method and is limited to fairly low Reynolds numbers and simplified geometries.
- LES works with coarser grids (only larger scales have to be resolved) and may be used to deal with higher Reynolds numbers but require subgrid scale models. The computation quality and the results accuracy are directly linked to these physical subgrid models.
- In current engineering practice, RANS is extensively used because it is less demanding in terms of resources but its validity is limited by the closure models describing turbulence and combustion

Poinsot T., Veynante D., *"Theoretical and Numerical Combustion"*, R.T. Edwards, 2nd Edition, 2005

Comparison: DNS, LES, and RANS

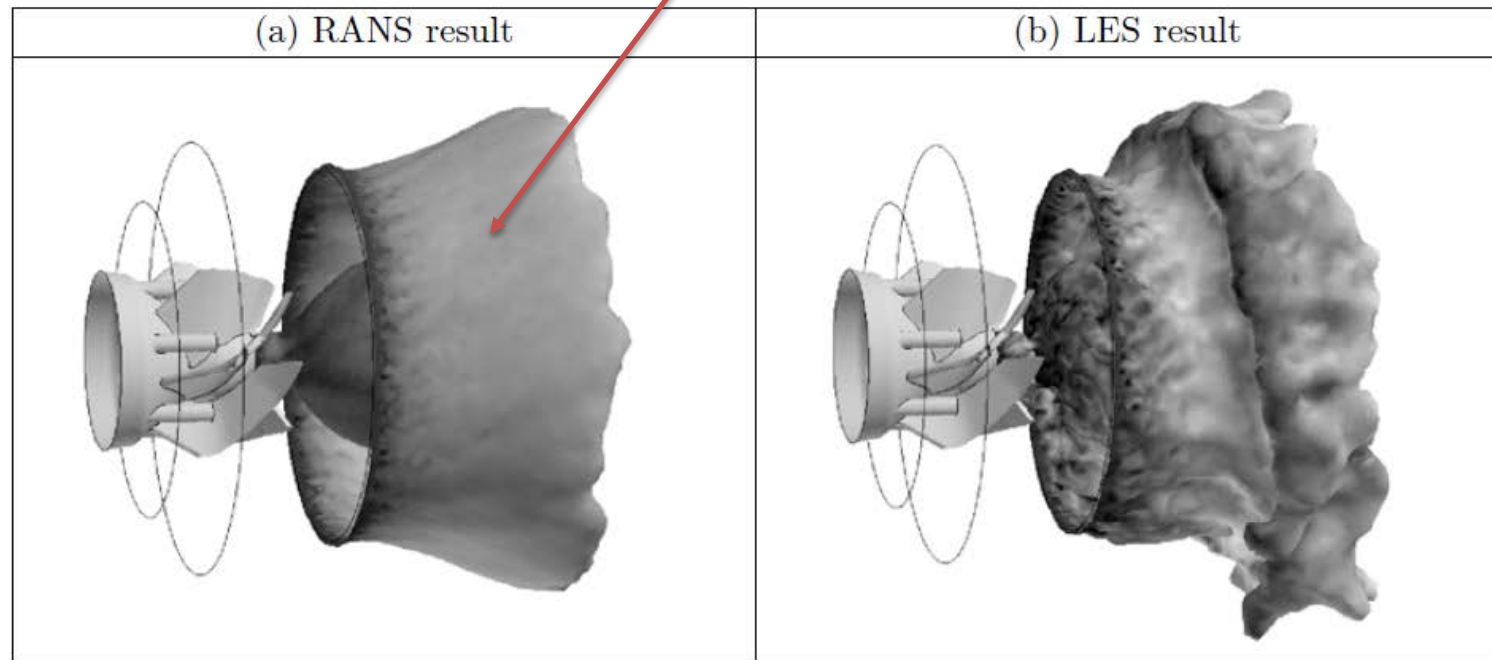
	Advantages	Drawbacks
RANS	<ul style="list-style-type: none">- Coarse numerical mesh- Geometrical simplifications (2D, symmetries, etc.)- Limited computational cost	<ul style="list-style-type: none">- Only mean flow fields- Closure models required
LES	<ul style="list-style-type: none">- Unsteady features- Reduced modelling impact (if compared to RANS)	<ul style="list-style-type: none">- Subgrid models required- 3D simulations- Advanced/accurate numerical techniques- Computational cost
DNS	<ul style="list-style-type: none">- No closure/subgrid models for turbulence and turbulence/combustion interactions- Tool to study closure models	<ul style="list-style-type: none">- Prohibitive computational cost- Limited to academic problems

Poinsot T., Veynante D., *"Theoretical and Numerical Combustion"*, R.T. Edwards, 2nd Edition, 2005

Computational advantages of RANS (I)

The advantage of RANS is its applicability to any configuration and operating conditions: a standard RANS mesh can contain $10^5 - 10^6$ cells and the domain of calculation may be as large as needed.

On the iso-surface, the average temperature is 1100 K but RANS does not explicitly solve for possible turbulent fluctuations around this mean value.



Iso-surface of mean high temperature (1100 K) in a turbulent premixed flame stabilized by swirl. (Selle et al., 2004).

Computational advantages of RANS (II)

The same example, simulated via a DNS, would be basically unfeasible. Indeed, while for the RANS simulation the cell size is $\sim 1 - 5 \text{ mm}$, for the DNS it would be $\sim 10 - 50 \text{ }\mu\text{m}$, i.e. ~ 100 times smaller. Thus, the required computational mesh (in terms of number of cells) would be $\sim 100^3 = 10^6$ times larger!

Why do similar problems treated with DNS and RANS require so different grid sizes?

- DNS has to describe the smallest scales contained in the flow field and to resolve the inner instantaneous structure of the flame front. This last condition determines the grid size. For hydrocarbon/air flames at atmospheric pressure, fronts have a thickness of the order of 0.1 mm so that mesh sizes of the order of μm are required.
- In contrast, RANS considers an average flame front which extends over a broader region: only mean turbulence characteristics and average statistical position of the front are solved for. Typical mean flame brushes in burners, aircraft or piston engine have a thickness of 1 to 2 cm and may be easily resolved with a 2 mm mesh.
- Engineering codes using RANS techniques (the majority of current computational tools) never resolve the inner structure of the flame and provide average flow fields featuring scales which are much larger than the instantaneous flame thickness.

Effect of fluctuations of formation rates (I)

The formation rate of each chemical species is a function highly non linear of temperature and composition (especially temperature)

$$r(\mathbf{C}, T) = k(T) \sum_i C_i^{\lambda_i} \quad k(T) = AT^n \exp\left(-\frac{E}{RT}\right)$$

Arrhenius' Law

This means that the mean formation rate is not equal to the reaction rate calculated at the mean values of temperature and composition:

$$\bar{r}(\mathbf{C}, T) = \bar{r}(\bar{\mathbf{C}} + \mathbf{C}', \bar{T} + T') \neq r(\bar{\mathbf{C}}, \bar{T})$$

This can be easily demonstrated if we perform a Taylor expansion around the mean values of temperature and composition:

$$\begin{aligned} r(\mathbf{C}, T) = r(\bar{\mathbf{C}} + \mathbf{C}', \bar{T} + T') &= r(\bar{\mathbf{C}}, \bar{T}) + \sum_{i=1}^{NS} \left. \frac{\partial r}{\partial C_i} \right|_{\bar{\mathbf{C}}, \bar{T}} C'_i + \left. \frac{\partial r}{\partial T} \right|_{\bar{\mathbf{C}}, \bar{T}} T' + \dots \\ &\dots + \frac{1}{2} \sum_{i=1}^{NS} \sum_{j=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial C_j} \right|_{\bar{\mathbf{C}}, \bar{T}} C'_i C'_j + \frac{1}{2} \left. \frac{\partial^2 r}{\partial T^2} \right|_{\bar{\mathbf{C}}, \bar{T}} T'^2 + \frac{1}{2} \sum_{i=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial T} \right|_{\bar{\mathbf{C}}, \bar{T}} C'_i T' + h.o. terms \end{aligned}$$

Effect of fluctuations of formation rates (II)

If we apply the mean:

$$\bar{r}(\mathbf{C}, T) \approx r(\bar{\mathbf{C}}, \bar{T}) + \dots$$

$$\dots + \underbrace{\frac{1}{2} \sum_{i=1}^{NS} \sum_{j=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial C_j} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{C'_i C'_j} + \frac{1}{2} \left. \frac{\partial^2 r}{\partial T^2} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{T'^2} + \sum_{i=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial T} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{C'_i T'}}_{\text{These terms have to be modelled}}$$

These terms have to be modelled, i.e. they have to be expressed as function of mean variables only

They are directly associated to the non linearity of formation rates with respect to the temperature and composition.

They are strongly dependent on the fluctuations of temperature and composition and in most cases are not negligible.

$$\bar{r}(\mathbf{C}, T) \approx r(\bar{\mathbf{C}}, \bar{T}) + C_C$$

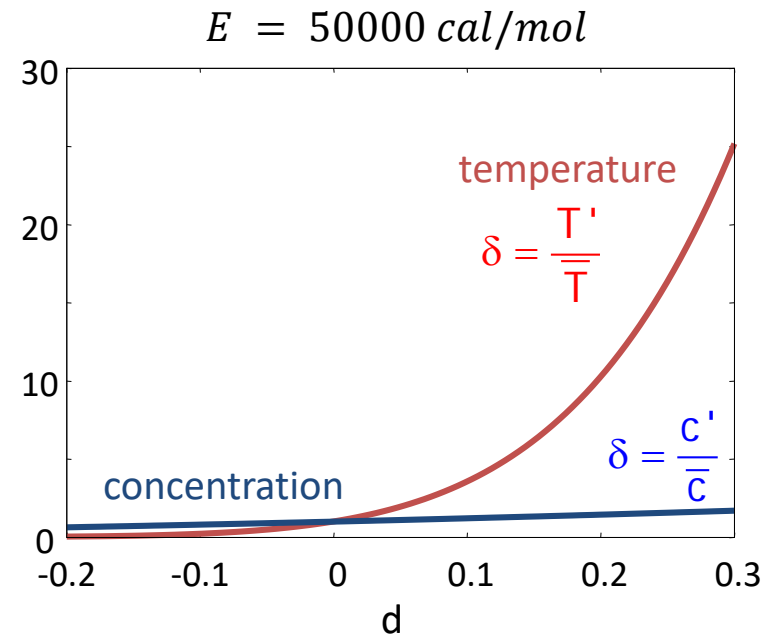
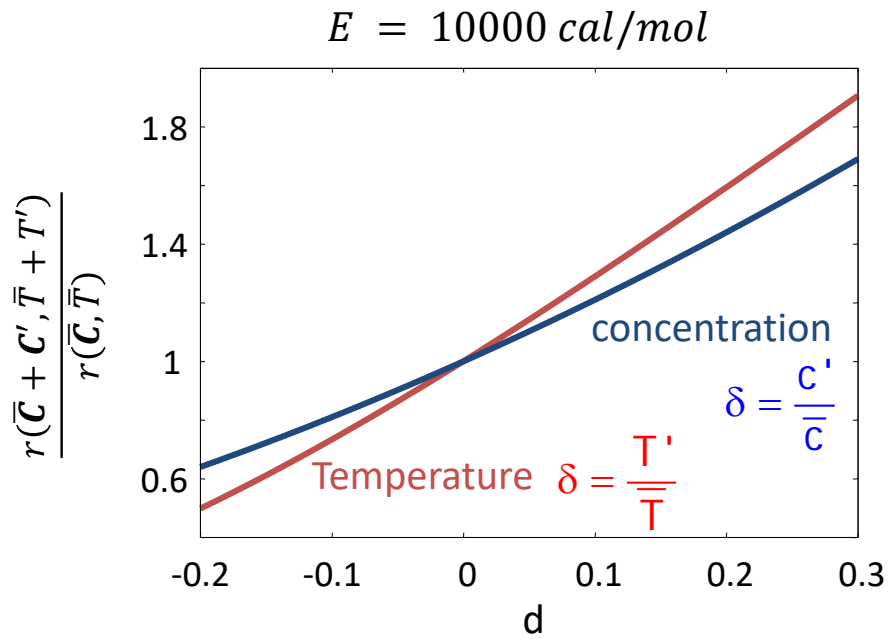
Is this term really relevant?

Temperature and composition fluctuations

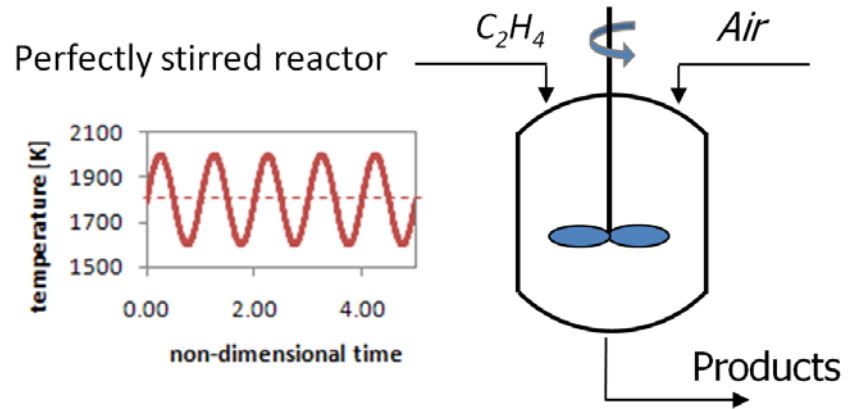
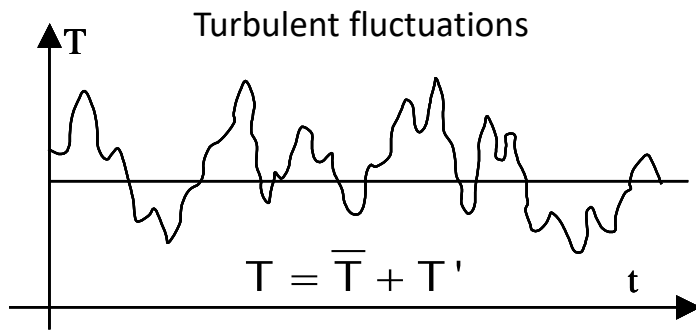
Temperature fluctuations have a strong impact especially on reactions with large activation energy
(as an example formation of NO_x)

Example: second order reaction

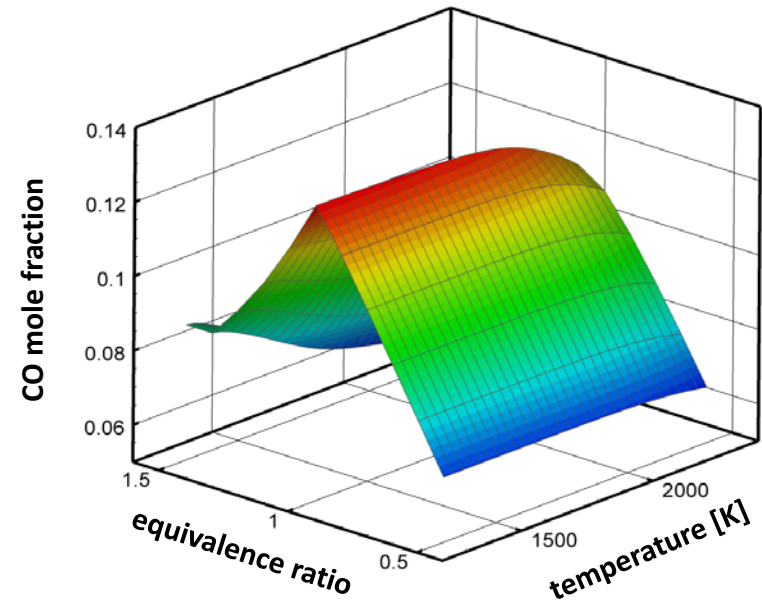
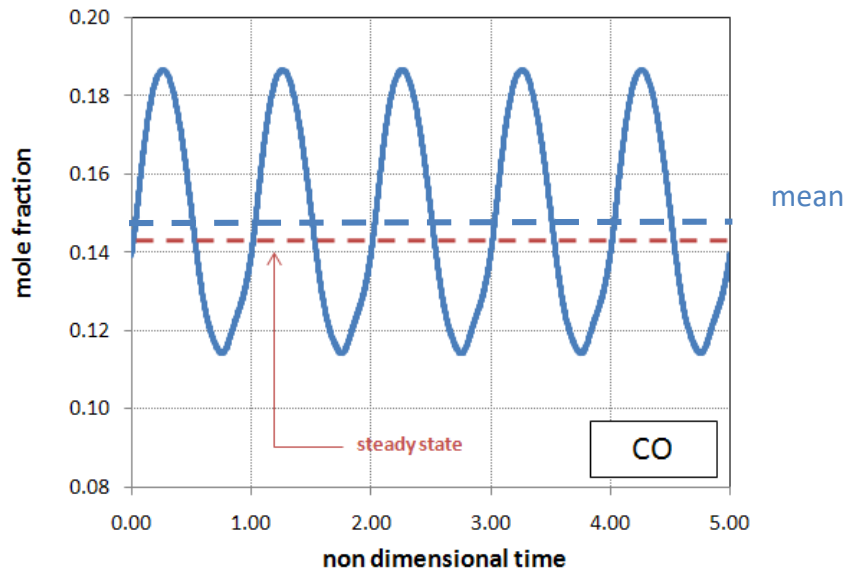
$$r(C, T) = A \exp\left(-\frac{E}{RT}\right) C^2$$



Effect of turbulent fluctuations (I)

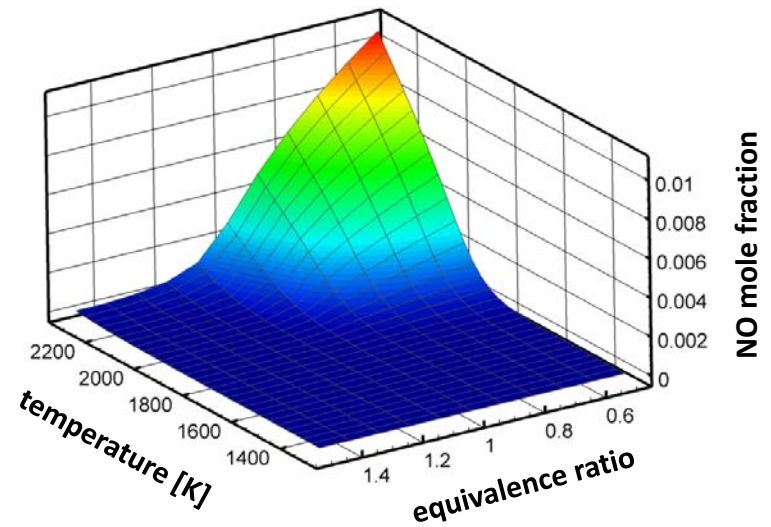
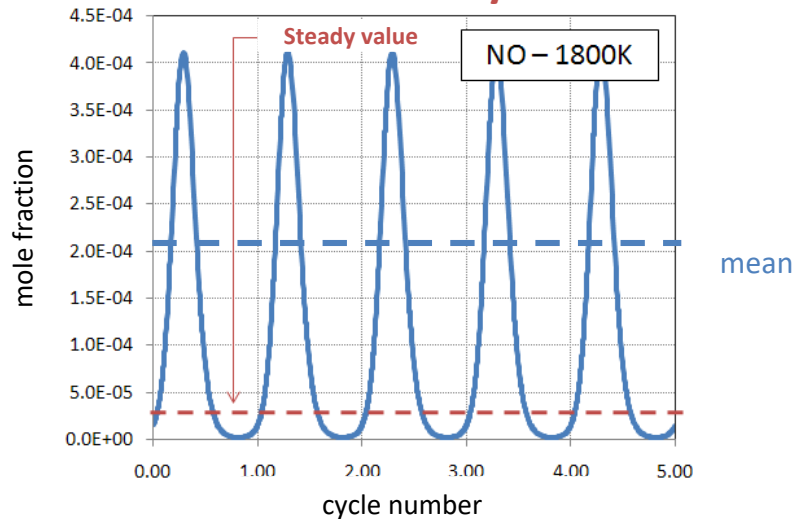


Fast chemistry: CO

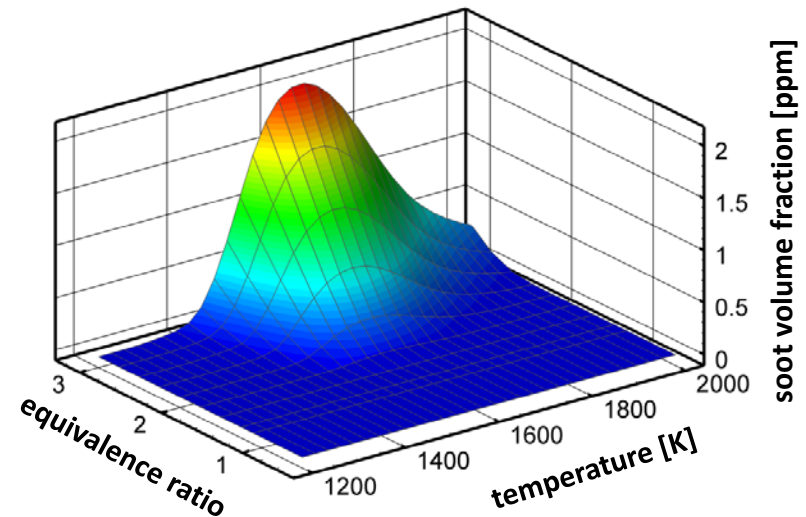
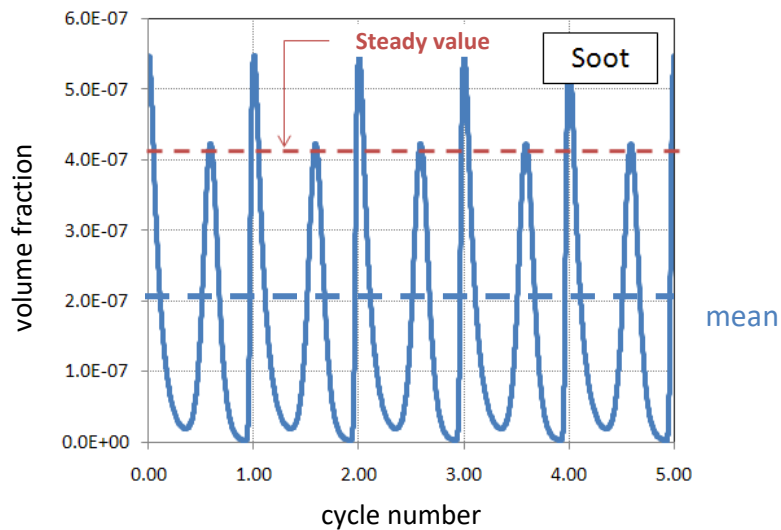


Effect of turbulent fluctuations (II)

Slow chemistry: NOx

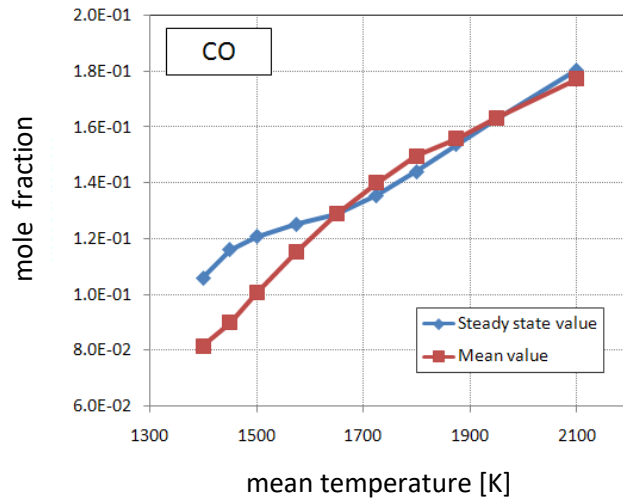


Finite-rate chemistry: Soot

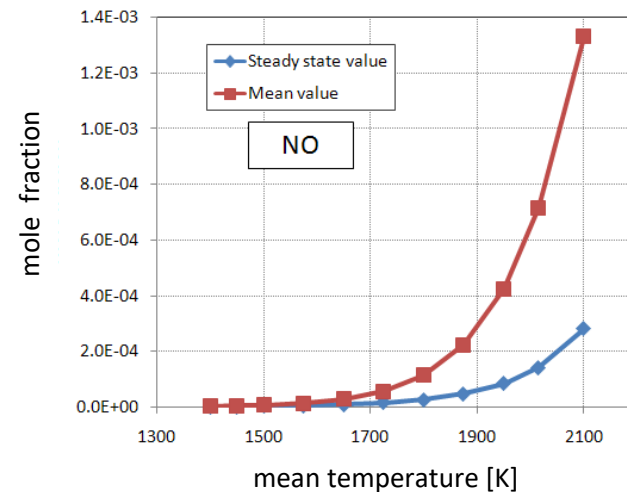


Effect of turbulent fluctuations (III)

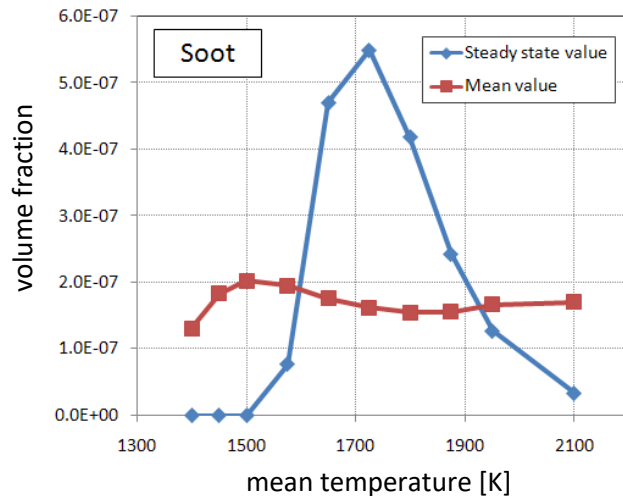
Fast chemistry: CO



Slow chemistry: NO



Finite-rate chemistry: Soot



The effect of fluctuation of temperature on soot production is quite complex to describe, since the dependence of soot on temperature is complex from a chemical point of view

A first, unsuccessful attempt to close mean reaction

Let's go back to the expansion previously carried out:

$$\bar{r}(\mathbf{C}, T) \approx r(\bar{\mathbf{C}}, \bar{T}) + \frac{1}{2} \sum_{i=1}^{NS} \sum_{j=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial C_j} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{C'_i C'_j} + \frac{1}{2} \left. \frac{\partial^2 r}{\partial T^2} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{T'^2} + \sum_{i=1}^{NS} \left. \frac{\partial^2 r}{\partial C_i \partial T} \right|_{\bar{\mathbf{C}}, \bar{T}} \overline{C'_i T'}$$

- It is clear that this direct approach to evaluate mean reaction rates, based on series expansion, cannot be applied for practical simulations.
- In particular, new quantities such as $\overline{C'_i C'_j}$, $\overline{C'_i T'}$, and $\overline{T'^2}$ have to be closed, using algebraic expressions or transport equations. Transport equations are unfeasible in case of large kinetic mechanisms: as an example, for $NS = 30$, we should write $30^2/2 = 450$ transport equations for the $\overline{C'_i C'_j}$ terms.
- For these reasons, reaction rate closures in turbulent combustion are not based on the equation above, but are derived from physical analysis.

Series expansion for 1-step, irreversible reaction

Nevertheless, the approach based on series expansion can be used in some practical simulations where chemical times are not negligible compared to flow times, for example in supersonic reacting flow or to describe chemical reactions in atmospheric boundary layer where the temperature T may be roughly assumed to be constant.

The approach is limited to the case of a single, irreversible reaction between fuel and oxidizer $F + sO \rightarrow P$.

The series expansion would give, arrested to second-order terms, gives:

$$\bar{r}(\mathbf{C}, T) \approx r(\bar{\mathbf{C}}, \bar{T}) + Q_{F,O} \overline{C'_F C'_O} + Q_F \overline{C'^2_F} + Q_O \overline{C'^2_O} + Q_T \overline{T'^2} + Q_{F,T} \overline{C'_F T'} + Q_{O,T} \overline{C'_O T'}$$

In the situations mentioned above, the most relevant expansion term is the first one (i.e. $Q_{F,O} \overline{C'_F C'_O}$). All the remaining terms are neglected. Thus, the average reaction rate is written as:

$$\bar{r}(\mathbf{C}, T) \approx r(\bar{\mathbf{C}}, \bar{T}) + Q_{F,O} \overline{C'_F C'_O} = r(\bar{\mathbf{C}}, \bar{T})(1 + \alpha_S)$$

The segregation factor α_S measures the mixing between fuel and oxidizer ($\alpha_S = 0$ for perfectly mixed reactants and $\alpha_S = -1$ for perfectly separated ones).

This factor is modeled or provided by a balance equation.

Series expansion for kinetic post-processing (I)

Rate constant is highly **non linear** function of temperature

$$k(T) = AT^n \exp\left(-\frac{E}{RT}\right)$$

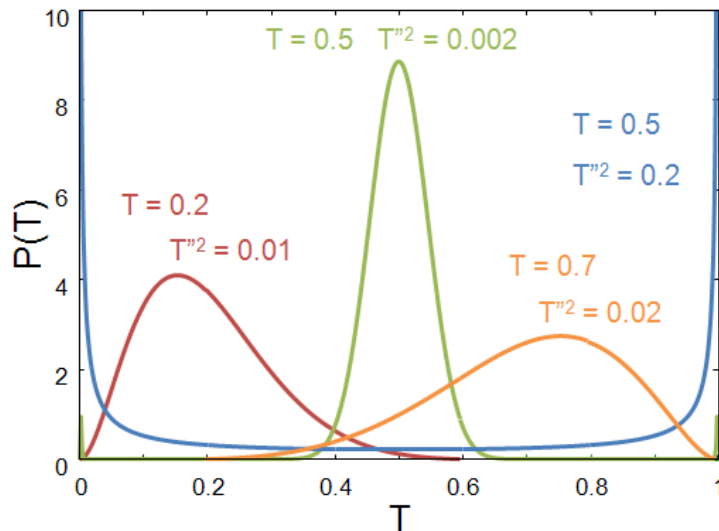


Introduction of a proper **probability distribution function** $p(T)$

$$\bar{k} = \int_{T_{min}}^{T_{max}} k(T)p(T)dT = C_C k(\bar{T})$$

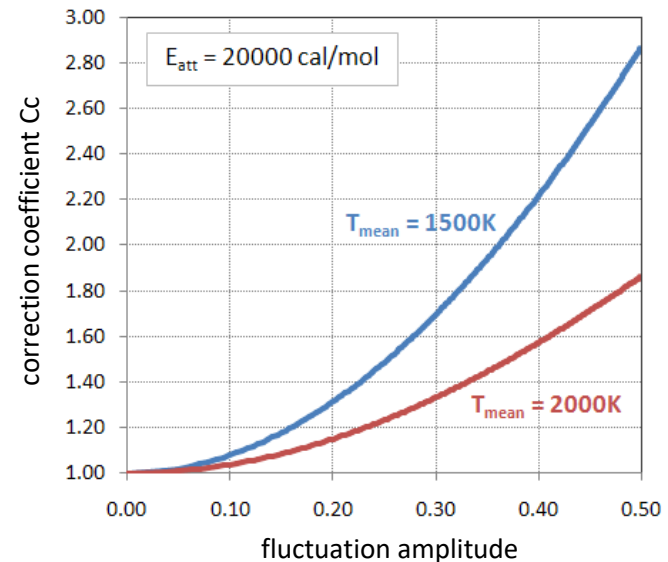
Requires the knowledge of the **variance of temperature**

β -PDF



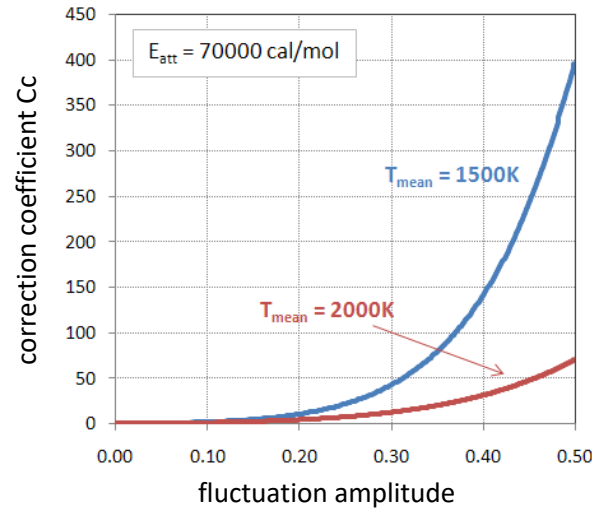
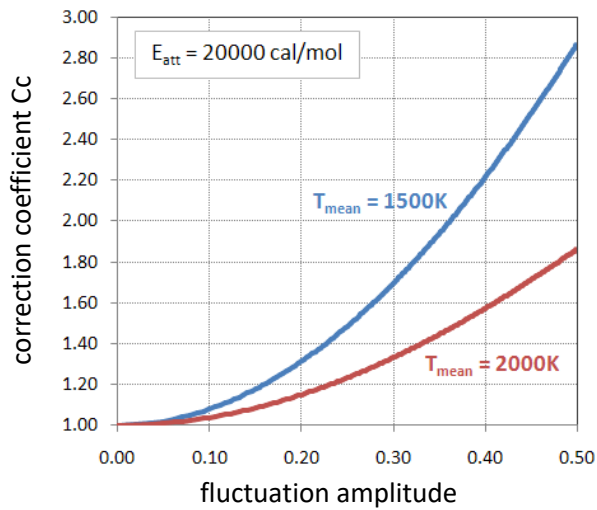
Correction coefficient

$$C_C = \frac{\int_{T_{min}}^{T_{max}} k(T)p(T)dT}{k(\bar{T})}$$

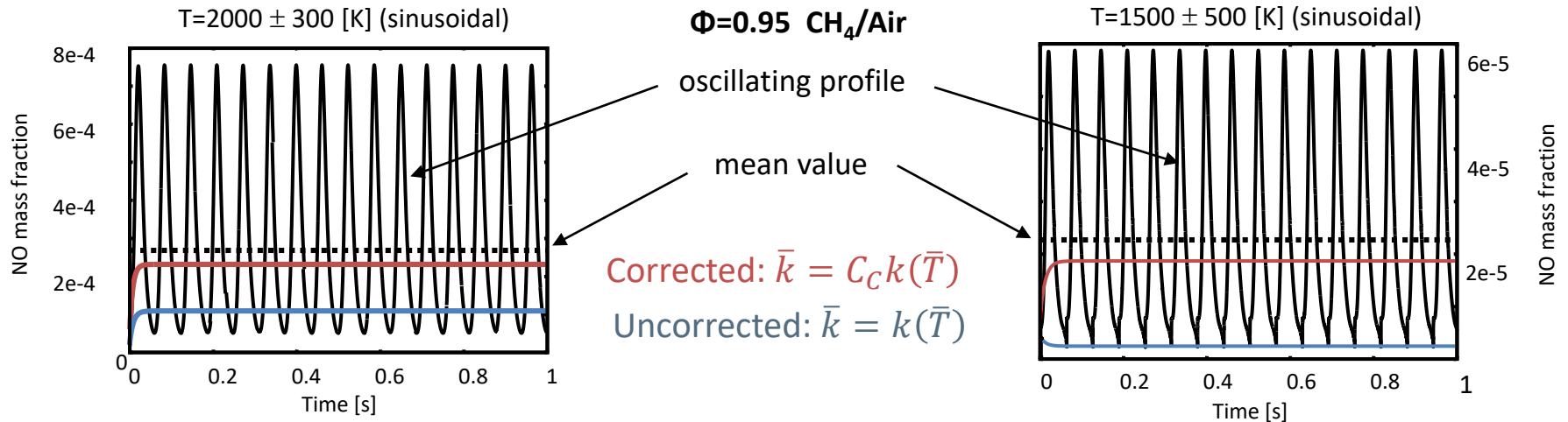


A. Cuoci, A. Frassoldati, G. Buzzi Ferraris, T. Faravelli, E. Ranzi,
International Journal of Hydrogen Energy (32), p. 3486-3500 (2007)

Series expansion for kinetic post-processing (II)



The correction Coefficient is significantly > 1 for high activation energies
(Thermal NO_x)



The error ($< 15\%$) is also due to the fluctuations of composition (neglected)

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2. Non-premixed combustion

- a) **Eddy Dissipation models: ED, ED-FR, EDC**
- b) Steady Laminar Flamelet model
 - i. Mixture fraction
 - ii. Flamelet equations
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3. Premixed combustion

- a) Eddy Break-Up (EBU) model
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- c) G-Equation

Turbulent combustion models

Infinitely Fast Chemistry Finite Rate Chemistry	1. Eddy Dissipation 2. Eddy Dissipation – Finite Rate	1. Fast Chemistry – PDF mixture fraction
	1. Eddy Dissipation Concept 2. Transported PDF Flamelet Model	1. Flamelet Approach
	Reaction Rates Approach (RRA)	Primitive Variables Approach (PVA)

Reaction rates approach (RRA)

- ✓ only the formation rates of species are modeled
- ✓ the formation rate is usually calculated on-line
- ✓ high computational cost
- ✓ very accurate
- ✓ able to describe non-conventional cases

Primitive variables approach (PVA)

- ✓ only a limited number of scalar variables, the primitive variables, must be solved
- ✓ no equations of conservation of species have to be solved
- ✓ the flame structure is solved before the fluid dynamic simulation and stored in so-called look-up tables
- ✓ low computational cost

Eddy Dissipation (ED) model (I)

- Most fuels are fast burning, and the overall rate of reaction is controlled by turbulent mixing.
- In non-premixed flames, turbulence slowly convects/mixes fuel and oxidizer into the reaction zones where they burn quickly. In premixed flames, the turbulence slowly convects/mixes cold reactants and hot products into the reaction zones, where reaction occurs rapidly.
- In such cases, the combustion is said to be mixing-limited, and the complex, and often unknown, chemical kinetic rates can be safely neglected.

Chemical regime

$$Da \ll 1$$

Chemical reactions extremely slow. The system is under chemical control

Fluid dynamic regime

$$Da \gg 1$$

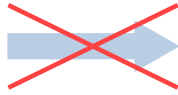
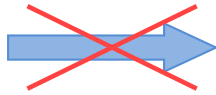

Chemical reactions extremely fast. The system is under fluid dynamic control


Eddy Dissipation (ED) model (II)

One-step non reversible reaction $F + rO \rightarrow (1 + r)P$

Fluid dynamic control

The reaction rate is controlled by the mixing velocity of fuel and oxidizer vortices

Fuel reaction rate	$\bar{r}_f = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_f$	
Oxidizer reaction rate	$\bar{r}_{ox} = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_{ox}$	
Product reaction rate	$\bar{r}_p = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_p$	

Reaction rate  $\bar{r} = \min \left(\bar{r}_f, \frac{\bar{r}_{ox}}{r}, \frac{\bar{r}_p}{1 + r} \right)$

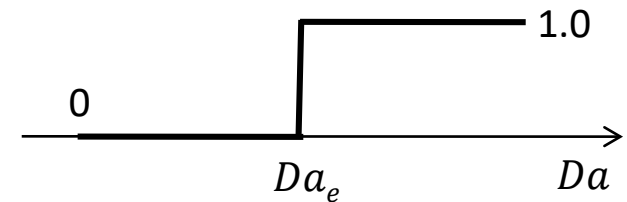
Magnussen B.F., Hjertager B.,H. "On mathematical modeling of turbulent combustion", 16th Symposium (International) on Combustion, 1976

Collision Mixing Model

$$\min \left(\bar{r}_f, \frac{\bar{r}_{ox}}{r}, \frac{\bar{r}_p}{1 + r} \right) \psi$$

Chemical control

Fluid dynamic control

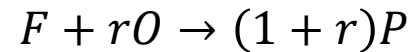


In order to take into account a possible chemical control

$$Da_e \sim 10^{-3}$$


Eddy Dissipation – Finite Rate (ED-FR) Model

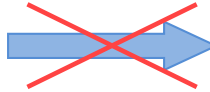
One-step non reversible reaction




Fluid dynamic control

The reaction rate is controlled by the mixing velocity of fuel and oxidizer vortices

Fuel reaction rate $\bar{r}_f = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_f$ 

Oxidizer reaction rate $\bar{r}_{ox} = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_{ox}$ 

Product reaction rate $\bar{r}_p = C_{ED} \bar{\rho} \frac{\tilde{\epsilon}}{\tilde{k}} \tilde{Y}_p$ 

Chemical control

Reaction rate expressed through the Arrhenius' Law

$$k_r = A \tilde{T}^n \exp\left(-\frac{E}{R \tilde{T}}\right)$$

$$\bar{r}_{chem} = k_r \prod C_i^{\eta_i}$$



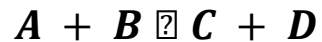
Reaction rate



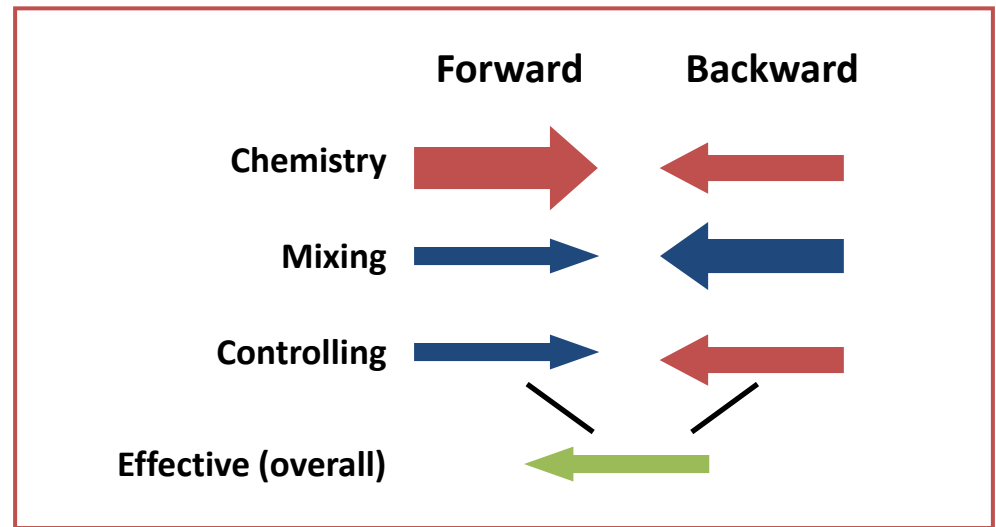
$$\bar{r} = \min\left(\bar{r}_f, \frac{\bar{r}_{ox}}{r}, \frac{\bar{r}_p}{1+r}, \bar{r}_{chem}\right)$$

Thermodynamically consistent ED-FR model

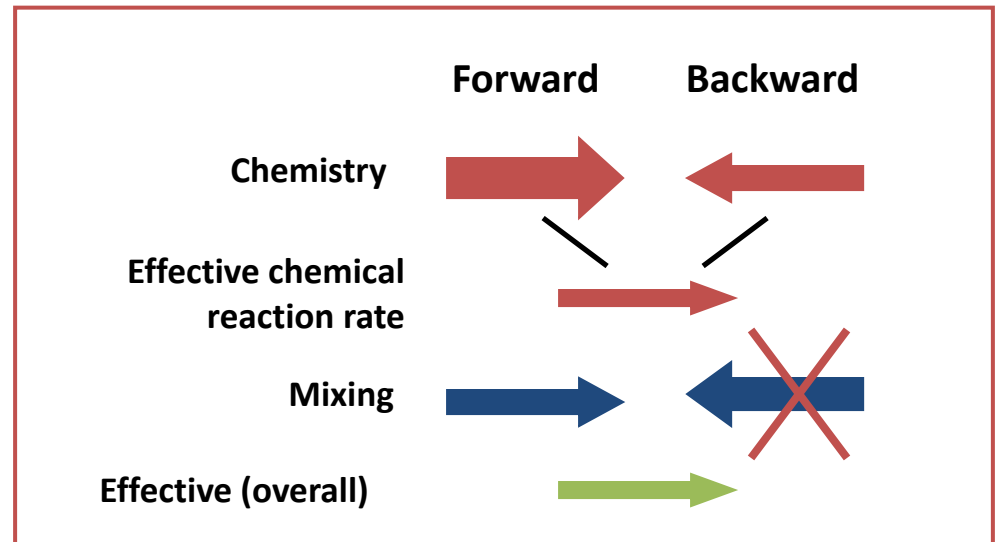
Reversible chemical reaction



Finite-Rate/Eddy-Dissipation



Consistent
Finite-Rate/Eddy-Dissipation



Eddy Dissipation Concept (EDC)

Fine Structures

Hp: Isotropic turbulence

$$\gamma_\lambda = 2.13 \left(\frac{\nu \varepsilon}{k^2} \right)^{1/4} \quad \text{Volume fraction of fine structures}$$

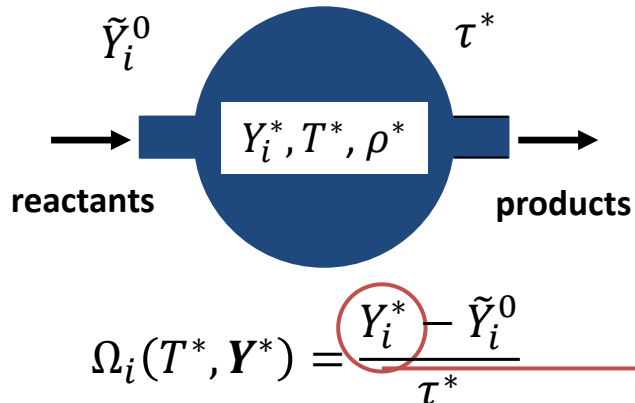
$$\tau^* = 0.4082 \left(\frac{\nu}{\varepsilon} \right)^{1/2} \quad \text{Mean residence time in the fine structures}$$



Homogeneous, isobaric reactors



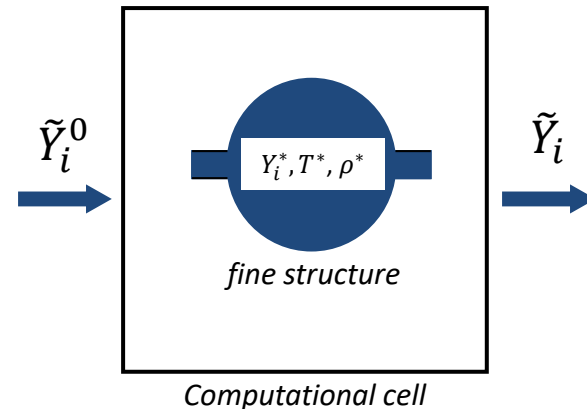
Steady-state perfectly stirred reactors



Gran I.R., Magnussen B.F. "A numerical study of a bluff-body stabilized diffusion flame", Combustion Science and Technology, 119 (1-6), 1996

RANS Variables

$$\bar{\rho} \quad \tilde{u} \quad \tilde{T} \quad \tilde{Y}_i \quad \tilde{k} \quad \tilde{\varepsilon}$$



$$\dot{\Omega}_i = \frac{\bar{\rho} \gamma_\lambda^3}{\tau^* (1 - \gamma_\lambda^3)} (Y_i^* - \tilde{Y}_i)$$

1. Introduction to turbulent combustion modeling

- a) Fluid dynamic and chemical time scales
- b) Effects of turbulent fluctuations on chemical reactions
- c) Need of turbulent combustion models

2. Non-premixed combustion

- a) Eddy Dissipation models: ED, ED-FR, EDC
- b) **Steady Laminar Flamelet model**
 - i. **Mixture fraction**
 - ii. **Flamelet equations**
 - iii. **Presumed PDF approach**

3. Premixed combustion

- a) Eddy Break-Up (EBU) model
- b) Bray-Libby-Moss (BLM) model
- c) G-Equation

The Steady State Flamelet (SSF) model

- Under certain assumptions, the thermochemistry can be reduced to a single parameter: **the mixture fraction**.
- The mixture fraction, denoted by **z** , is the mass fraction that originated from the fuel stream. In other words, it is the local mass fraction of burnt and unburnt fuel stream elements (C, H, etc.) in all the species (CO_2 , H_2O , O_2 , etc.).
- The approach is elegant because atomic elements are conserved in chemical reactions. In turn, the mixture fraction is a conserved scalar quantity, and therefore its governing transport equation **does not have a source term**.
- Combustion is simplified to a **mixing problem**, and the difficulties associated with closing non-linear mean reaction rates are avoided. Once mixed, the chemistry can be modeled as being in chemical equilibrium with the Equilibrium model, being near chemical equilibrium with the Steady Laminar Flamelet model.

The mixture fraction (I)

One-step non reversible reaction $F + rO \rightarrow (1 + r)P$

Simplifying assumptions

- Unitary Lewis' numbers for all the species
- Constant specific heat (i.e. independent of temperature)

Conservation
equation of species

$$\rho \frac{\partial Y_k}{\partial t} + \rho u_i \frac{\partial Y_k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial Y_k}{\partial x_i} \right) + \dot{\Omega}_k$$

Conservation
equation of energy

$$\rho \frac{\partial T}{\partial t} + \rho u_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\lambda}{C_p} \frac{\partial T}{\partial x_i} \right) + \frac{\dot{q} \dot{\Omega}_f}{C_p}$$

Poinsot T., Veynante D., *"Theoretical and Numerical Combustion"*, Edwards, 2001

Peters N., *"Turbulent Combustion"*, Cambridge University Press, 2000

The mixture fraction (II)

Let's define 3 dimensionless variables as proper linear combinations of mass fractions and T:

Z_1	Z_2	Z_3
$Z_1 \stackrel{\text{def}}{=} rY_f - Y_o$	$Z_2 \stackrel{\text{def}}{=} \frac{C_P T}{\dot{q}} + Y_f$	$Z_3 \stackrel{\text{def}}{=} r \frac{C_P T}{\dot{q}} + Y_o$
$\rho \frac{\partial Z_j}{\partial t} + \rho u_i \frac{\partial Z_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial Z_j}{\partial x_i} \right)$		

Passive scalar	Fuel side	Oxidizer side
Z_1	rY_f^{in}	$-Y_o^{in}$
Z_2	$\frac{C_P T_f^{in}}{\dot{q}} + Y_f^{in}$	$\frac{C_P T_o^{in}}{\dot{q}}$
Z_3	$r \frac{C_P T_f^{in}}{\dot{q}}$	$r \frac{C_P T_o^{in}}{\dot{q}} + Y_o^{in}$

Fuel stream $Y_o^{in} \quad T_o^{in}$



Oxidizer stream $Y_o^{in} \quad T_o^{in}$

The mixture fraction (III)

$$\xi_j \stackrel{\text{def}}{=} \frac{Z_j - Z_{j,o}^{\text{in}}}{Z_{j,f}^{\text{in}} - Z_{j,o}^{\text{in}}}$$

Let us define new variables ξ_j corresponding to the normalized Z_j variables previously defined

It is easy to demonstrate analytically that the new ξ_j are governed by the same transport equation, without any source term (i.e. passive scalars)

$$\rho \frac{\partial \xi_j}{\partial t} + \rho u_i \frac{\partial \xi_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial \xi_j}{\partial x_i} \right)$$

The interesting point is to recognize that the boundary conditions for the three ξ_j are exactly the same, which means that actually they are the same variable, which is called the mixture fraction ξ :

$$\rho \frac{\partial \xi}{\partial t} + \rho u_i \frac{\partial \xi}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial \xi}{\partial x_i} \right) \quad \begin{cases} \xi(\text{fuel stream}) = 1 \\ \xi(\text{ox stream}) = 1 \end{cases}$$

The mixture fraction (IV)

It is clear that instead of solving the transport equations for all the species (F, O, and P) and for the temperature, we can solve only the mixture fraction transport equation and reconstruct from it every variable of interest:

$$\rho \frac{\partial \xi}{\partial t} + \rho u_i \frac{\partial \xi}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial \xi}{\partial x_i} \right)$$



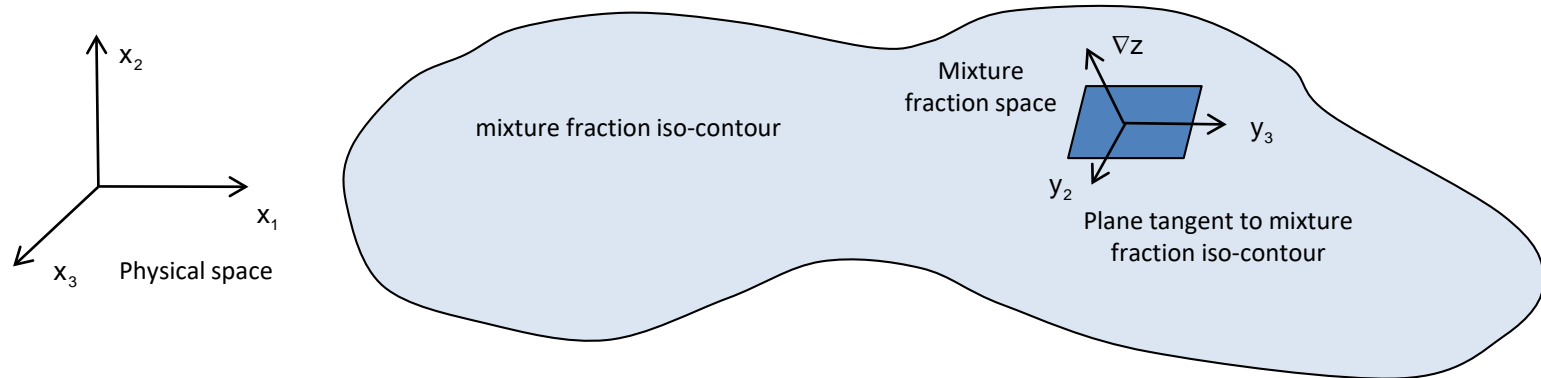
$$Z_j = Z_{j,o}^{in} + (Z_{j,f}^{in} - Z_{j,o}^{in})\xi$$



$$\begin{bmatrix} r & -1 & 0 \\ 1 & 0 & \frac{C_P}{\dot{q}} \\ 0 & 1 & r \frac{C_P}{\dot{q}} \end{bmatrix} \begin{bmatrix} Y_f \\ Y_o \\ T \end{bmatrix} = \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix}$$


Flame structure in z-space (I)

Poinsot T., Veynante D., "Theoretical and Numerical Combustion", Edwards, 2001

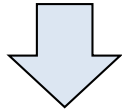


1. Species equations are rewritten in the (ξ, y_2, y_3, t) space, where y_2 and y_3 are spatial variables in planes parallel to iso- ξ surfaces
2. In the resulting equations, the terms corresponding to gradients along the flame front (i.e. along y_2 and y_3) are neglected in comparison to the terms normal to the flame
3. This means that we are assuming that **the flame structure is locally 1D**, depending only on t and on ξ (i.e. the flame is thin compared to other flow scales)
4. Each element of the flame front can then be viewed as a small laminar flame called **flamelet**

Flame structure in z-space (II)

$$\frac{\partial \rho Y_k}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i Y_k) = \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial Y_k}{\partial x_i} \right) + \dot{\Omega}_k$$


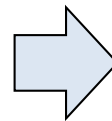
$$\rho \frac{\partial Y_k}{\partial t} + Y_k \left[\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) \right] + \frac{\partial Y_k}{\partial \xi} \left[\rho \frac{\partial \xi}{\partial t} + \rho u_i \frac{\partial \xi}{\partial x_i} - \frac{\partial}{\partial x_i} \left(\rho \mathcal{D} \frac{\partial \xi}{\partial x_i} \right) \right] - \rho \mathcal{D} \left(\frac{\partial \xi}{\partial x_i} \frac{\partial \xi}{\partial x_i} \right) \frac{\partial^2 Y_k}{\partial \xi^2} = \dot{\Omega}_k$$



Unsteady flamelet equations

$$\rho \frac{\partial Y_k}{\partial t} = \rho \mathcal{D} \left(\frac{\partial \xi}{\partial x_i} \frac{\partial \xi}{\partial x_i} \right) \frac{\partial^2 Y_k}{\partial \xi^2} + \dot{\Omega}_k$$

$$\rho \frac{\partial T}{\partial t} = \rho \mathcal{D} \left(\frac{\partial \xi}{\partial x_i} \frac{\partial \xi}{\partial x_i} \right) \frac{\partial^2 T}{\partial \xi^2} + \frac{\dot{Q}}{C_P}$$



Flame structure

$$Y_k = Y_k(t, \xi)$$

$$T = T(t, \xi)$$

The unsteady flamelet equation

$$\rho \frac{\partial Y_k}{\partial t} = \frac{1}{2} \rho \chi \frac{\partial^2 Y_k}{\partial \xi^2} + \dot{\Omega}_k$$

The flamelet equations are typically rewritten introducing the **scalar dissipation rate** χ , defined as:

$$\rho \frac{\partial T}{\partial t} = \frac{1}{2} \rho \chi \frac{\partial^2 T}{\partial \xi^2} + \frac{\dot{Q}}{C_P}$$

$$\chi = 2\mathcal{D} \left(\frac{\partial \xi}{\partial x_i} \frac{\partial \xi}{\partial x_i} \right)$$

- The flamelet equations are key elements in many diffusion flame theories: in these equations, the only term depending on spatial variables x_i is the scalar dissipation rate χ which controls mixing (because it controls the gradients of ξ).
- Once χ is specified, the flamelet equations can be entirely solved in the ξ space to provide the flame structure, i.e. $Y_k = Y_k(t, \xi)$ and $T = T(t, \xi)$
- Although this is not explicit in the present notation, the T and Y_k functions are parametrized by the scalar dissipation rate: different scalar dissipation levels lead to different flame structures.
- The scalar dissipation rate has the dimension of an inverse time (like strain). It measures the ξ -gradients and the molecular fluxes of species towards the flame.

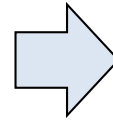
Steady flamelet equations

The structure of the flamelet can be assumed to be steady, even though the flow itself (and especially the ξ field) depends on time.

Unsteady flamelet equations

$$\frac{1}{2}\rho\chi\frac{\partial^2 Y_k}{\partial \xi^2} + \dot{\Omega}_k = 0$$

$$\frac{1}{2}\rho\chi\frac{\partial^2 T}{\partial \xi^2} + \frac{\dot{Q}}{C_p} = 0$$



Flame structure

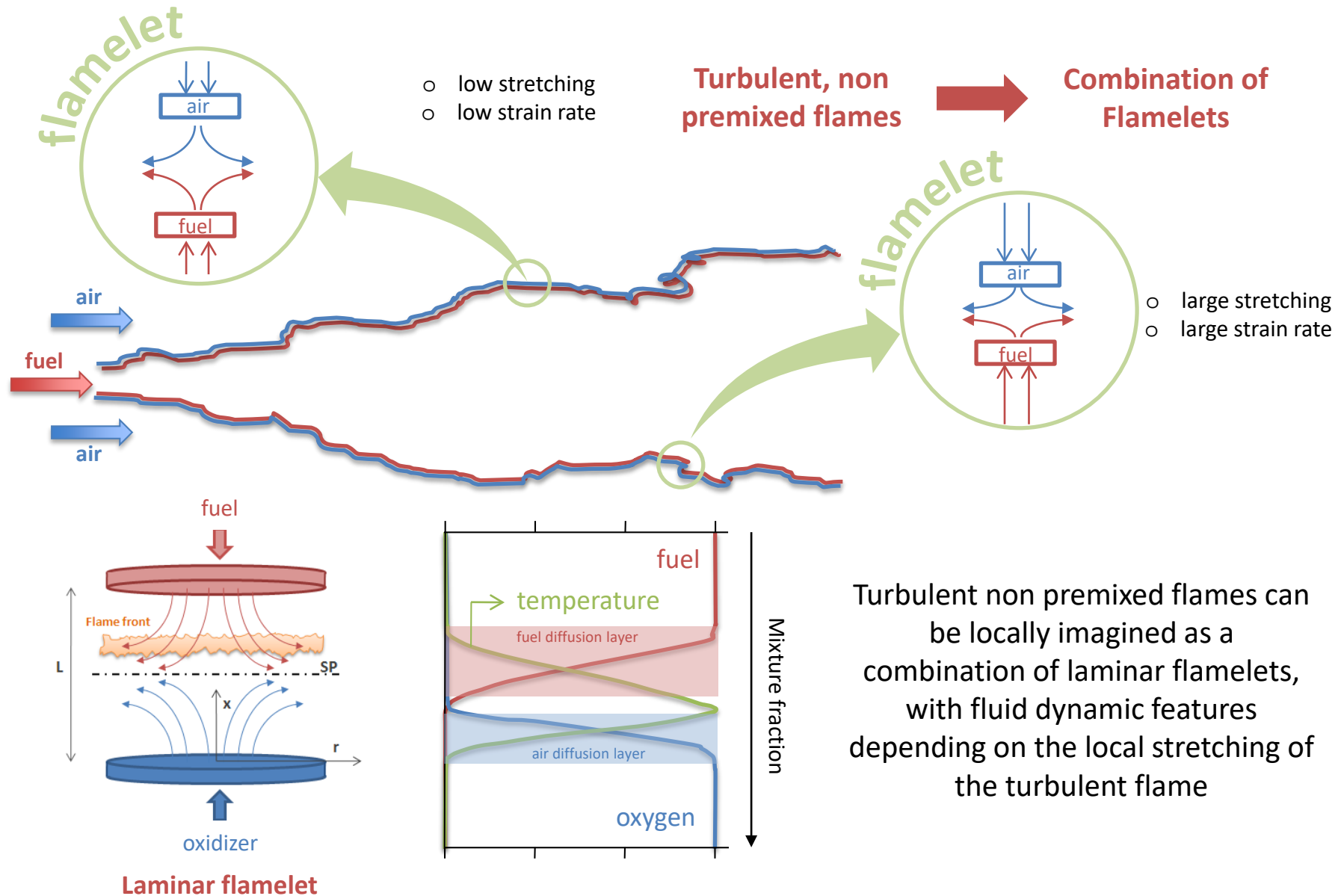
$$Y_k = Y_k(\xi, \chi)$$

$$T = T(\xi, \chi)$$

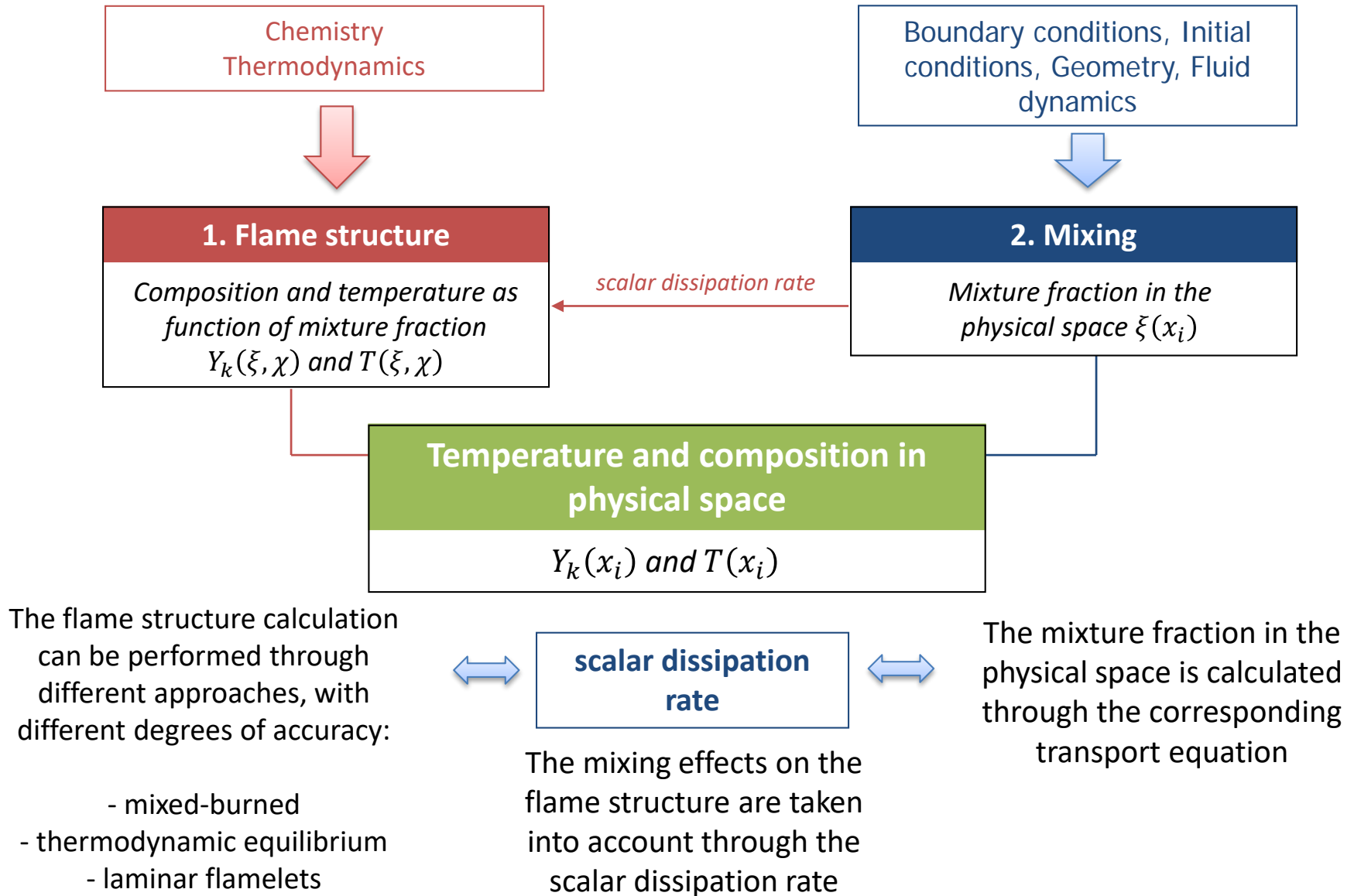
Reaction rates for species or temperature depend on ξ and χ only. Flow information is entirely contained in the scalar dissipation rate χ whereas chemical effects are incorporated through the flame structure in ξ -space.

This important simplification is emphasized in the following slides.

Physical interpretation



Flame Structure + Mixing



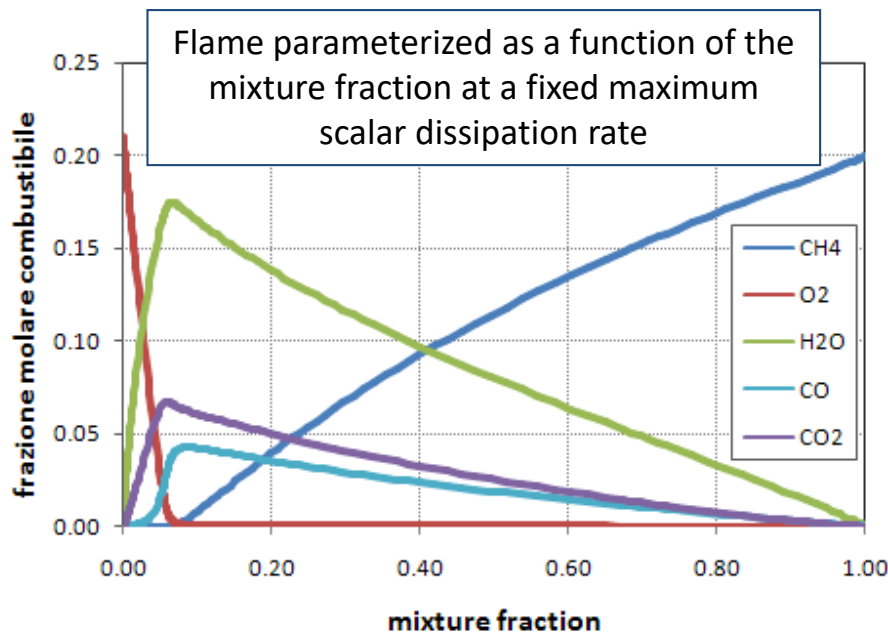
Flame structure (I)

The steady state flamelet equations are solved directly in the mixture fraction space

$$\frac{1}{2}\rho\chi\frac{\partial^2 Y_k}{\partial \xi^2} + \dot{\Omega}_k = 0 \qquad \frac{1}{2}\rho\chi\frac{\partial^2 T}{\partial \xi^2} + \frac{\dot{Q}}{C_P} = 0$$

The scalar dissipation rate is usually written as a function of the mixture fraction

$$\chi = \chi_0 e^{-2\left(\text{erf}^{-1}(1-2\xi)\right)^2}$$



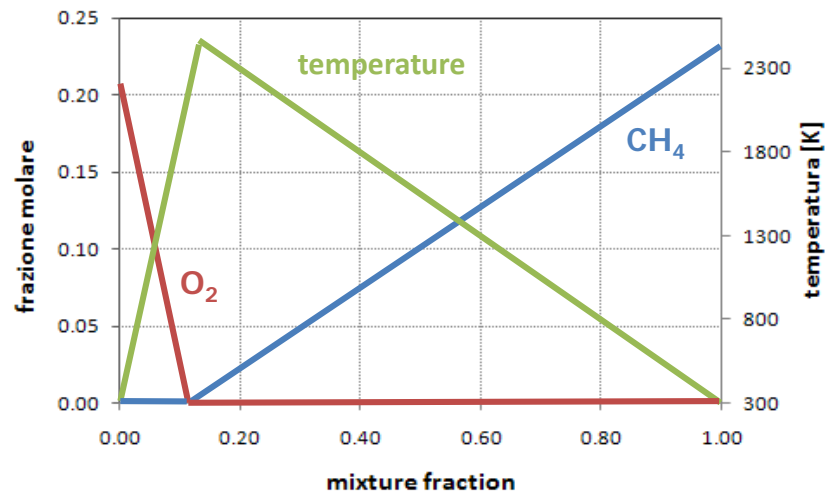
Pros

- Low computational resources
- Satisfactory accuracy for fast species

Cons

- Unitary Lewis' numbers for all the species (no differential diffusion)
- Not appropriate for slow species (as an example nitrogen oxides)

Flame structure (II)

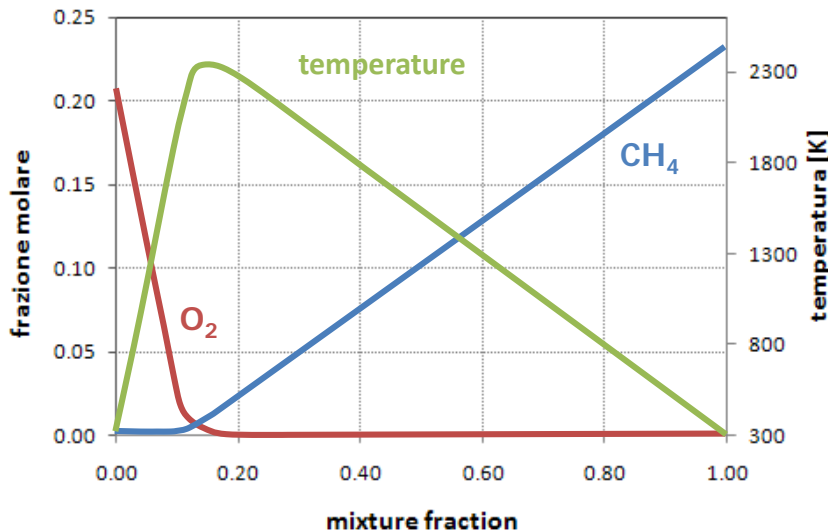


Approx. Solution: Mixed Is Burned

If we assume an infinitely fast one-step chemical reaction, the flamelet equations have the Burke-Schumann analytical solution

The solution does not depend on the scalar dissipation rate

Fuel and oxygen cannot co-exist

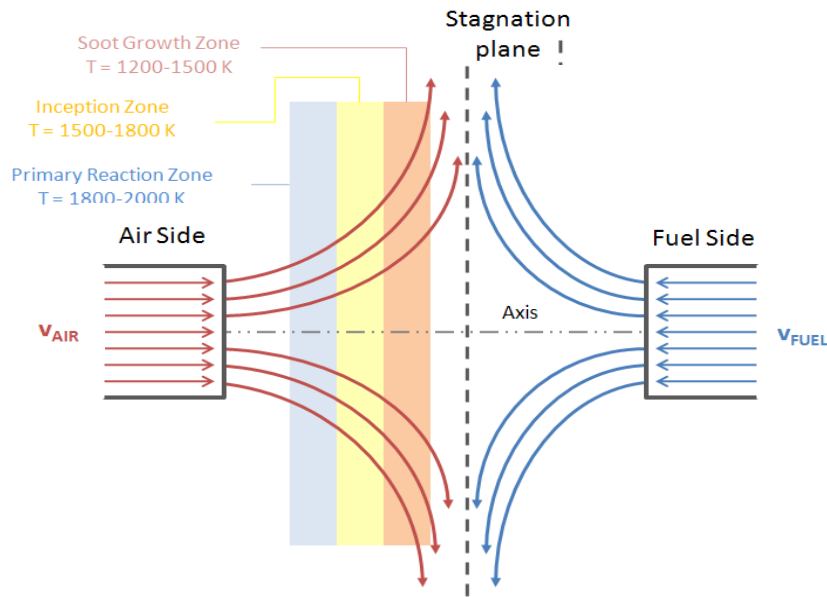


Approx. Solution: Equilibrium

This is the flamelet solution if the scalar dissipation rate approaches zero

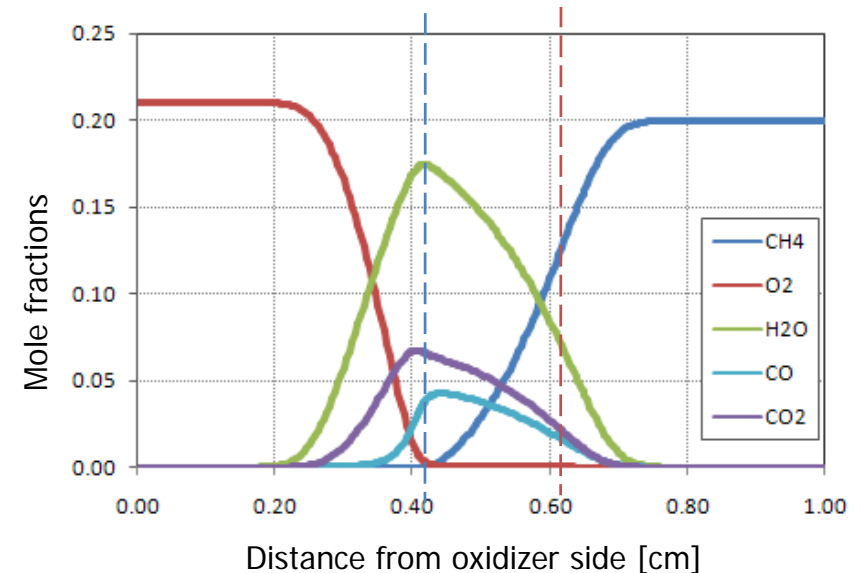
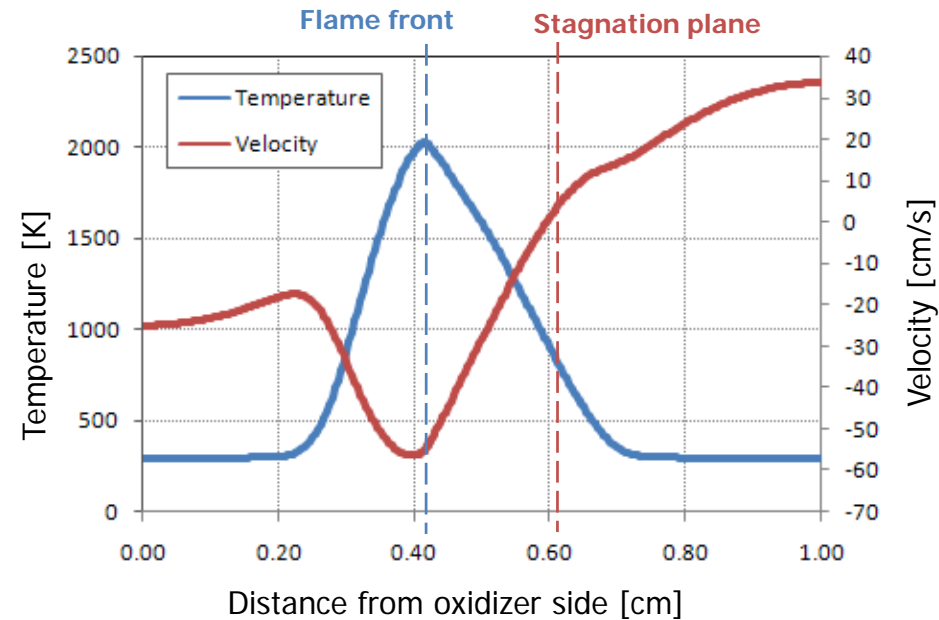
The solution does not depend on the scalar dissipation rate

Laminar counter-flow diffusion flames

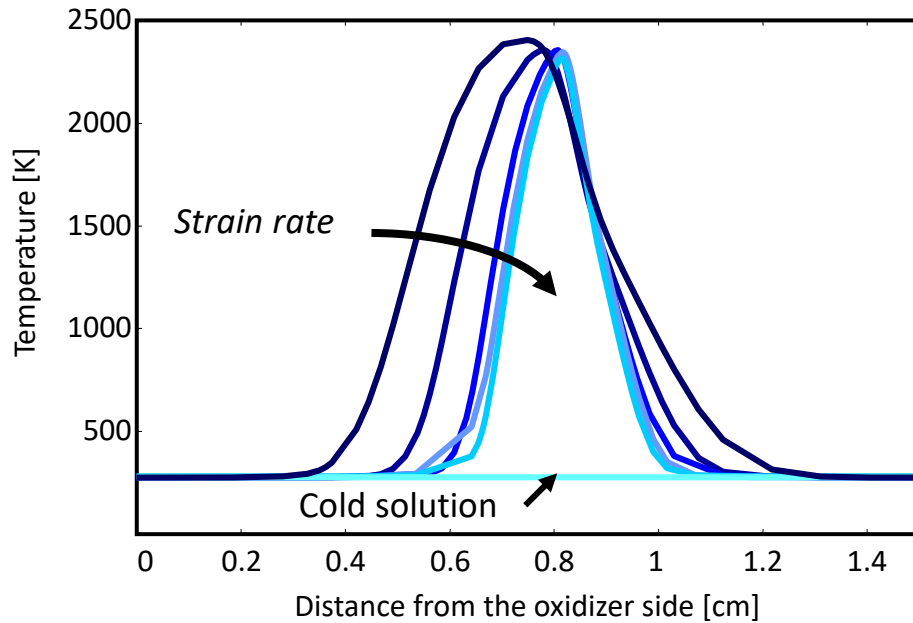


Usually, for conventional combustion in air, the flame front is on the oxidizer side

Peaks of temperature and main products can be usually find at the location of stoichiometric composition



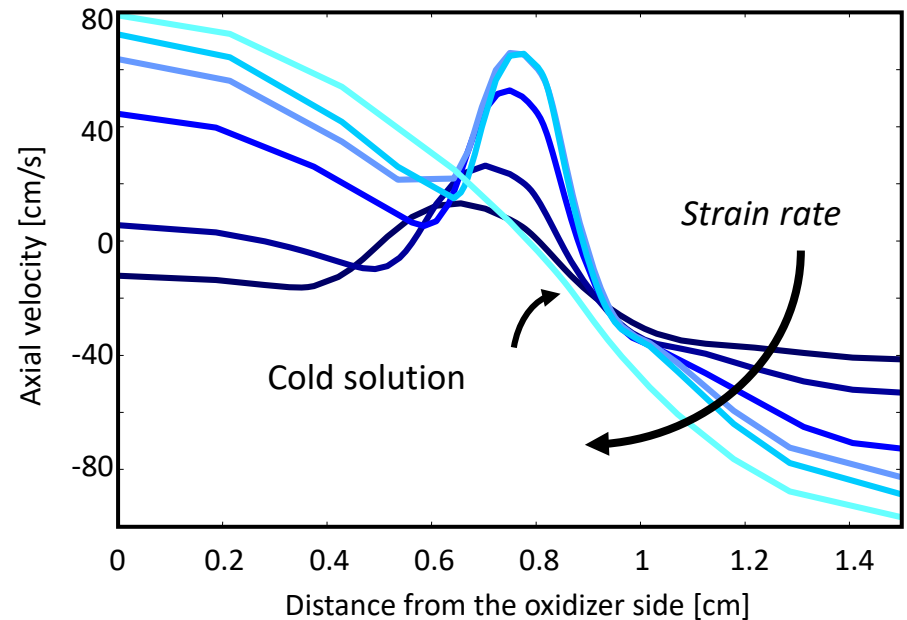
Strain rate



If we increase the strain rate, the residence time decreases. If we exceed the maximum strain rate the flame extinguishes.

Strain rate is a measure of the residence time

$$K = \frac{2v_o}{L} \left(1 + \frac{v_c}{v_o} \left(\frac{\rho_c}{\rho_o} \right)^{0.5} \right)$$



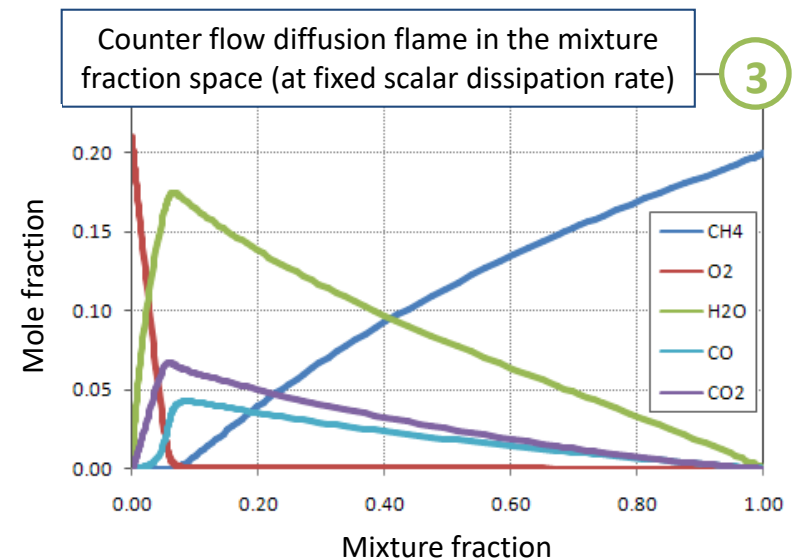
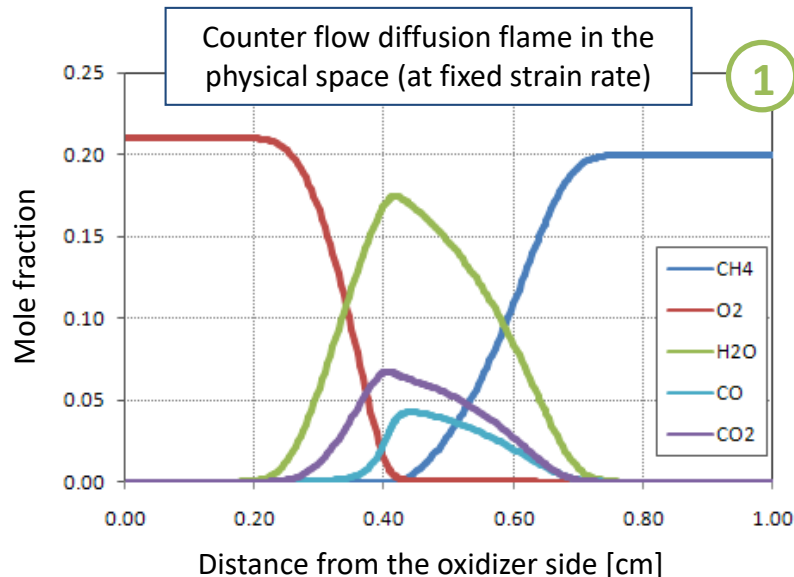
Flame structure (I)

Solution: Counter-Flow Diffusion Flames

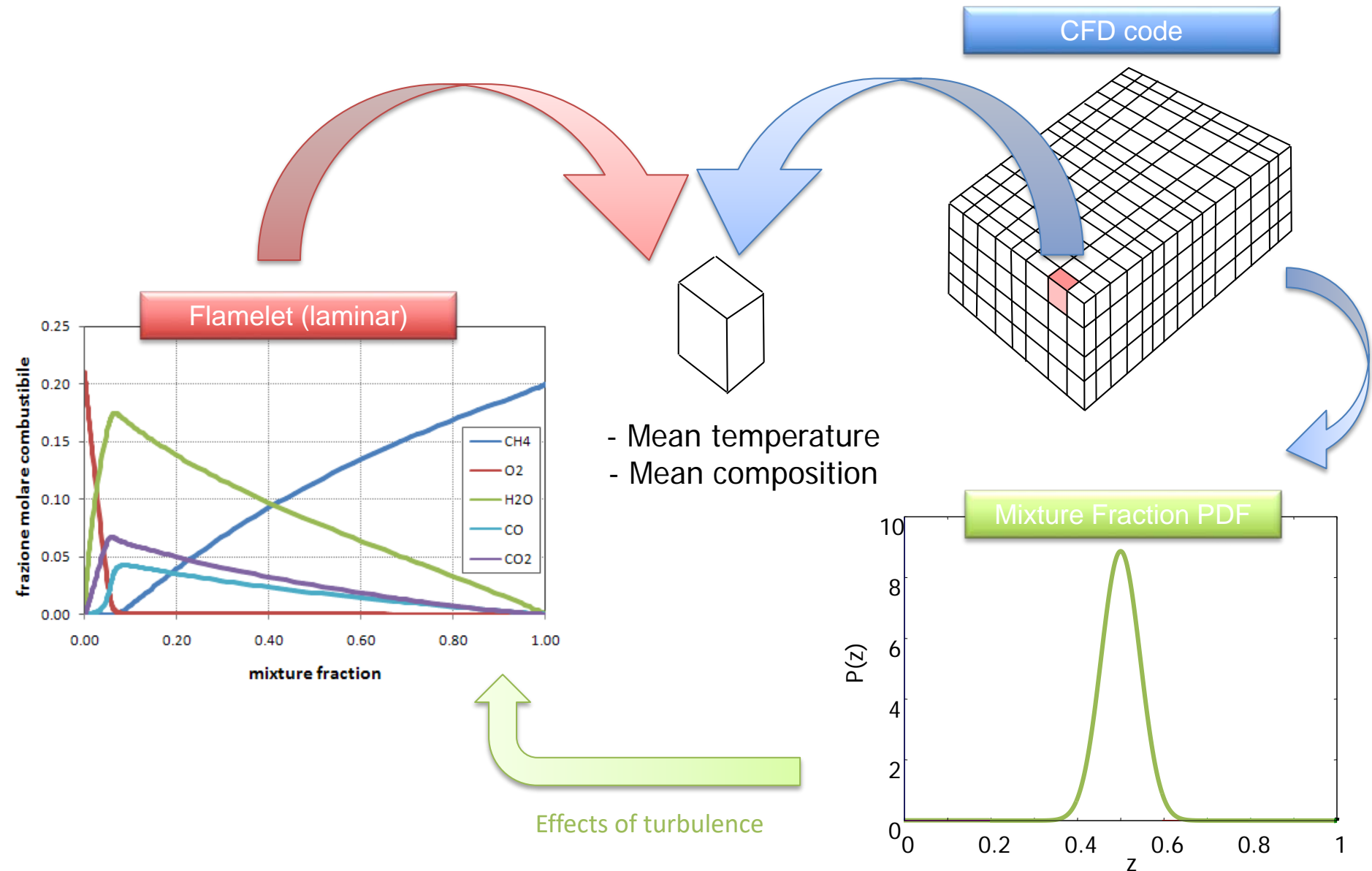
1. Counter-flow diffusion flame at fixed strain rate
2. **mixture fraction** is calculated in each point of the physical space
3. The solution is rewritten as a function of the **mixture fraction**

Usually the flame structures are parameterized as a function of the mixture fraction and the maximum scalar dissipation rate χ_0

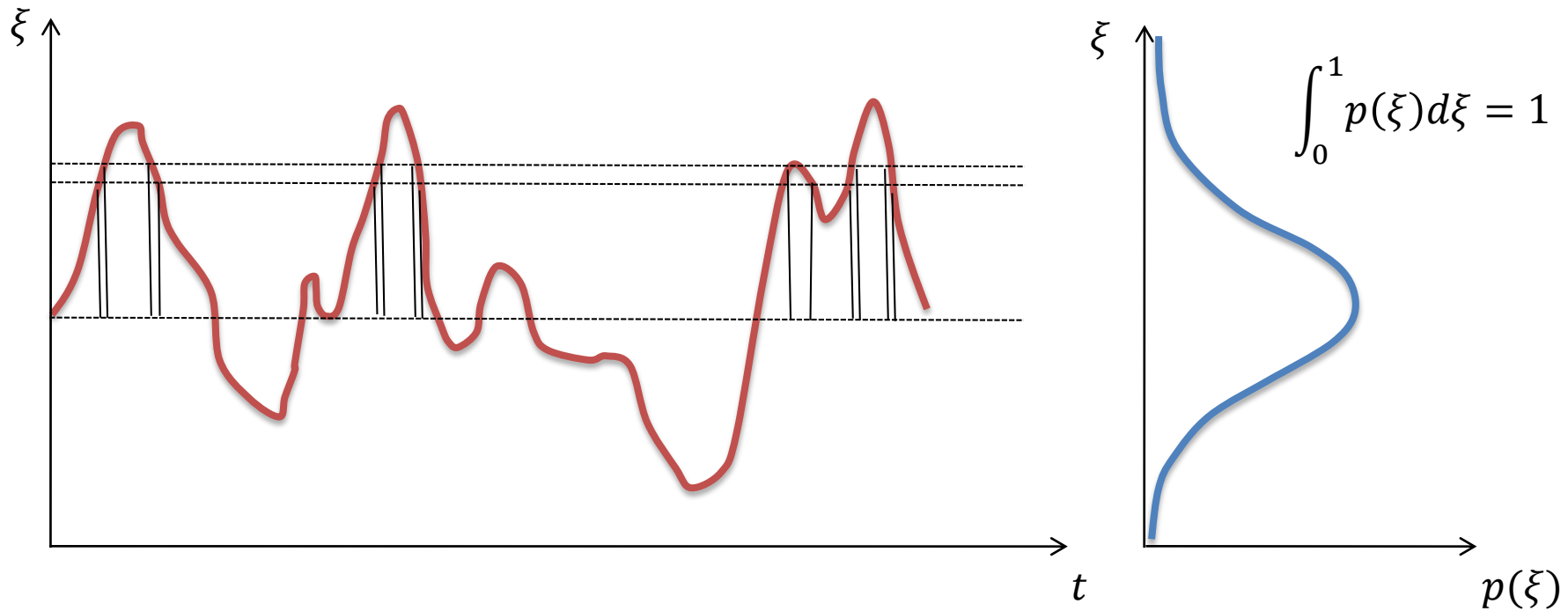
$$\chi_0 = \frac{a_S}{\pi} \quad \text{scalar dissipation rate and strain rate}$$



Coupling CFD - Flamelets



Probability Distribution Function (PDF)



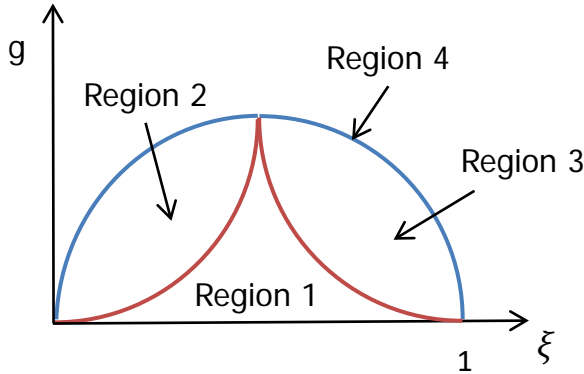
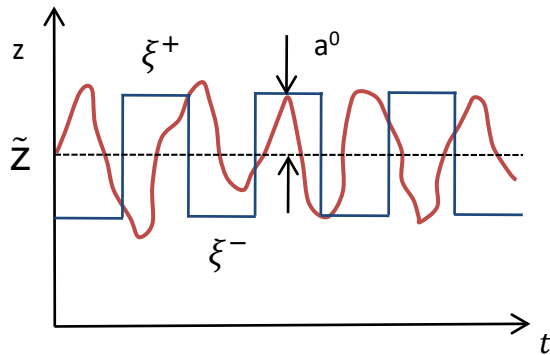
$$\bar{\xi} = \int_0^1 \xi p(\xi) d\xi$$

mean

$$g = \overline{\xi'^2} = \int_0^1 (\xi - \bar{\xi})^2 p(\xi) d\xi$$

variance

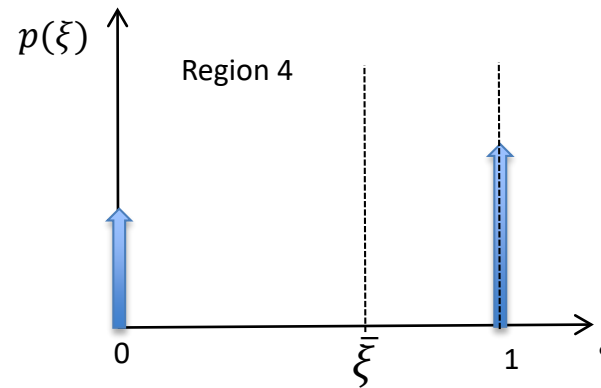
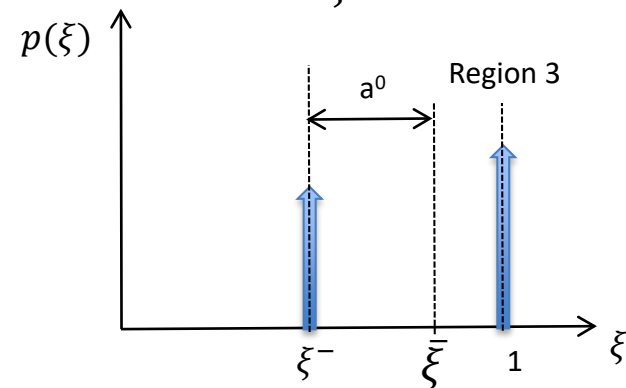
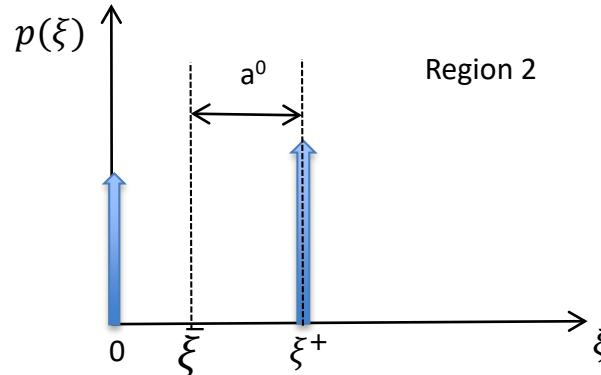
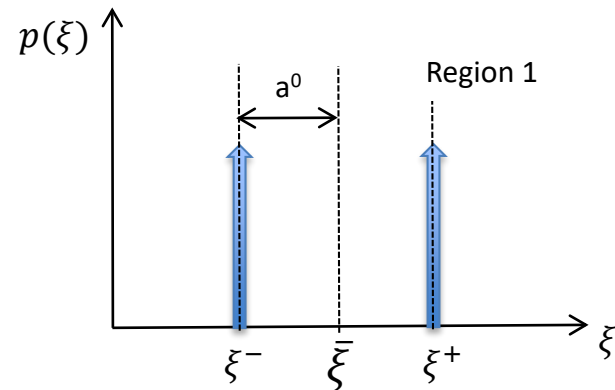
Double Delta Function (I)



Intermittent signal
between ξ^- and ξ^+

Usually not
accurate

Computational
cost negligible



Yeoh G.H., Yuen K.K.,
“Computational Fluid
Dynamics in Fire Engineering
Theory, Modelling and
Practice”, Butterworth-
Heinemann Ltd, 2009

Double Delta Function (II)

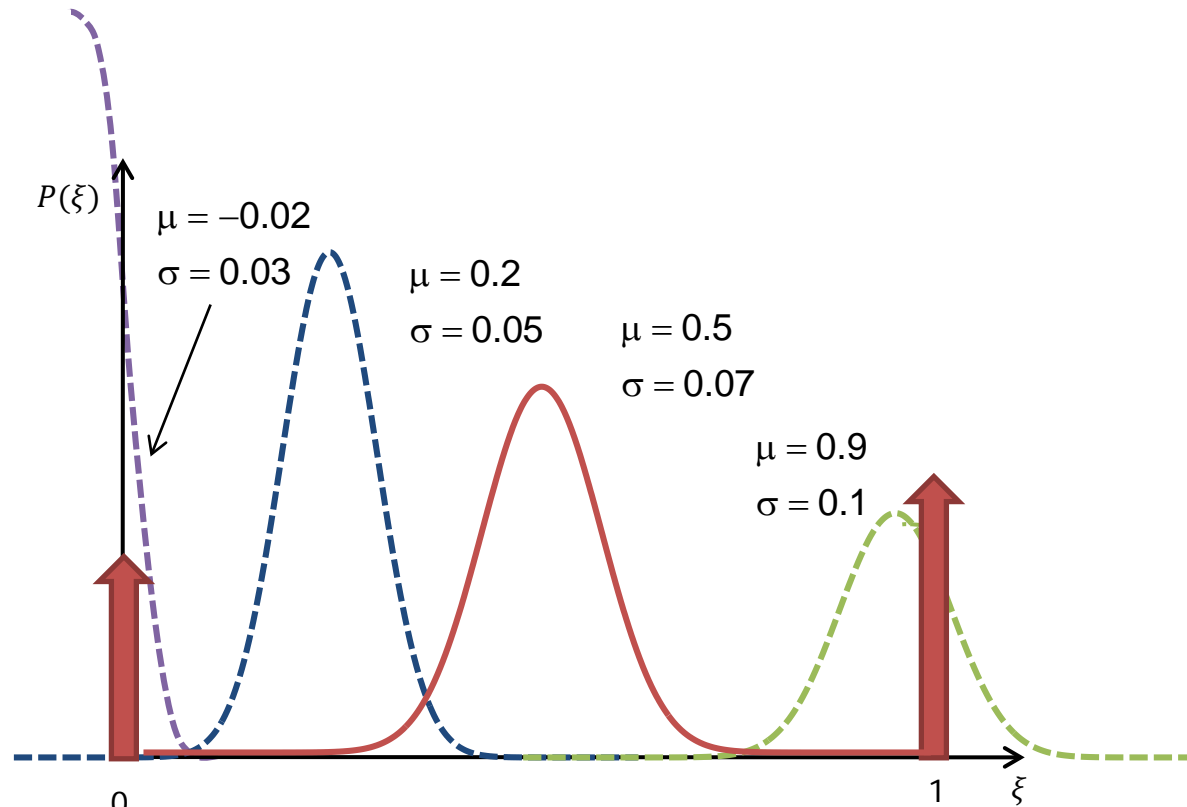
Region 1	Region 2
$p(\xi) = \frac{1}{2} \delta(\xi^-) + \frac{1}{2} \delta(\xi^+)$ $\begin{cases} \xi^- = \bar{\xi} - \sqrt{g} \\ \xi^+ = \bar{\xi} + \sqrt{g} \end{cases}$	$p(\xi) = \frac{1 - \bar{\xi}}{1 - \bar{\xi} + \frac{g}{1 - \bar{\xi}}} \delta(\xi^-) + \frac{g}{(1 - \bar{\xi})^2 + g} \delta(1)$ $\begin{cases} \xi^- = \bar{\xi} - \sqrt{g} \\ \xi^+ = 1 \end{cases}$
Region 3	Region 4
$p(\xi) = \left(\frac{g}{g + \bar{\xi}^2} \right) \delta(0) + \left(\frac{\bar{\xi}}{\bar{\xi} + \frac{g}{\bar{\xi}}} \right) \delta(\xi^+)$ $\begin{cases} \xi^- = 0 \\ \xi^+ = \bar{\xi} + \sqrt{g} \end{cases}$	$p(\xi) = (1 - \bar{\xi}) \delta(0) + \bar{\xi} \delta(1)$ $g = \bar{\xi}(1 - \bar{\xi})$

Clipped Gaussian

The Gaussian probability distribution function cannot be directly applied because the mixture fraction is a scalar which is defined between 0 and 1



The solution is a **Clipped Gaussian**, i.e. a modified Gaussian distribution defined between 0 and 1 and coupled with two delta Dirac functions at $z=0$ (pure oxidizer) and $z=1$ (pure fuel)



$$p(\xi) = A_0 \delta(0) + \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\xi - \mu}{\sigma} \right)^2 \right] [H(\xi) - H(\xi - 1)] + A_1 \delta(1)$$

$$A_0 = \int_{-\infty}^0 \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\xi - \mu}{\sigma} \right)^2 \right] d\xi$$

$$A_1 = \int_1^{+\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\xi - \mu}{\sigma} \right)^2 \right] d\xi$$

The most appropriate probability distribution function is the **β-PDF**

$$p(\xi) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \xi^{a-1} (1-\xi)^{b-1}$$

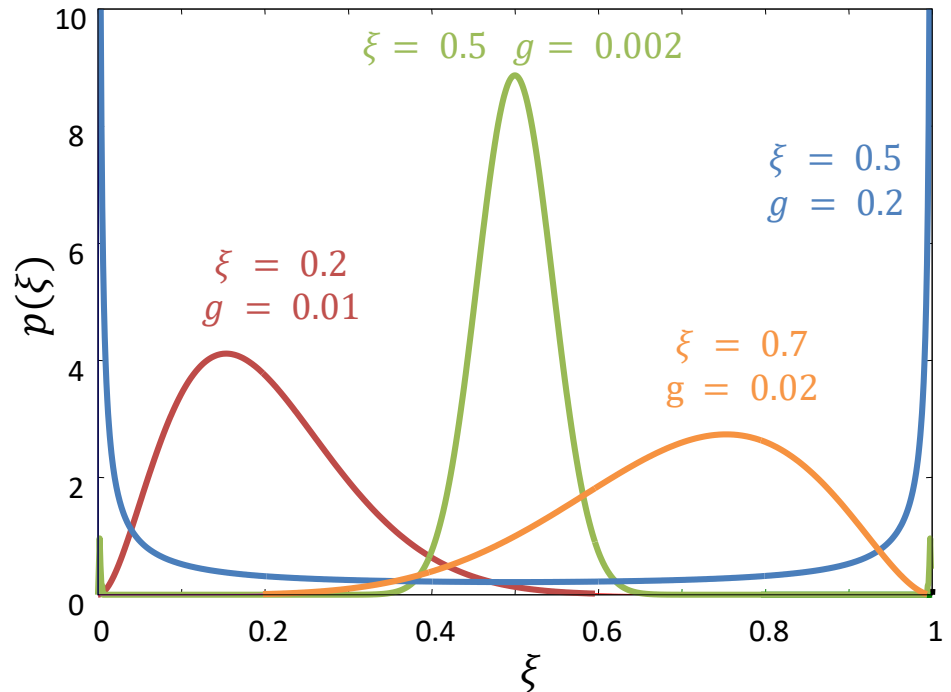
Where the Γ function is:

$$\Gamma(x) = \int_0^{\infty} e^{-t} t^{x-1} dt$$

The parameters **a** and **b** can be estimated from the mean value of mixture fraction and its variance

$$a = \tilde{\xi} \left[\frac{\tilde{\xi}(1-\tilde{\xi})}{g} - 1 \right]$$

$$b = \frac{a}{\tilde{\xi}} - a$$



The b-PDF is physically appropriate to model the real probability distribution function of mixture fraction.

The behavior is similar to a double delta Dirac if the variance is extremely large.

On the contrary, the behavior is similar to a Gaussian PDF when the variance is small.

Mixing

The mixture fraction field can be calculated through the solution of the corresponding transport equation in the physical space:

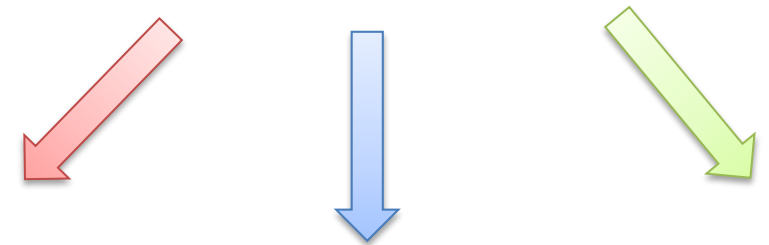
**Transport equation
of mixture fraction**

$$\bar{\rho} \frac{\partial \tilde{\xi}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \tilde{\xi}}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\bar{\rho} \mathcal{D}_t \frac{\partial \tilde{\xi}}{\partial x_i} \right)$$

The mixture fraction field is not enough to solve the turbulent flame problem. The fluctuations of mixture fraction must be also estimated:

**Transport equation
of mixture fraction
variance**

$$\bar{\rho} \frac{\partial \widetilde{\xi'^2}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \widetilde{\xi'^2}}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\bar{\rho} \mathcal{D}_t \frac{\partial \widetilde{\xi'^2}}{\partial x_i} \right) + 2 \bar{\rho} \mathcal{D}_t \left(\frac{\partial \tilde{\xi}}{\partial x_i} \right)^2 - \bar{\rho} C_\chi \frac{\tilde{\epsilon}}{\tilde{k}} \widetilde{\xi'^2}$$

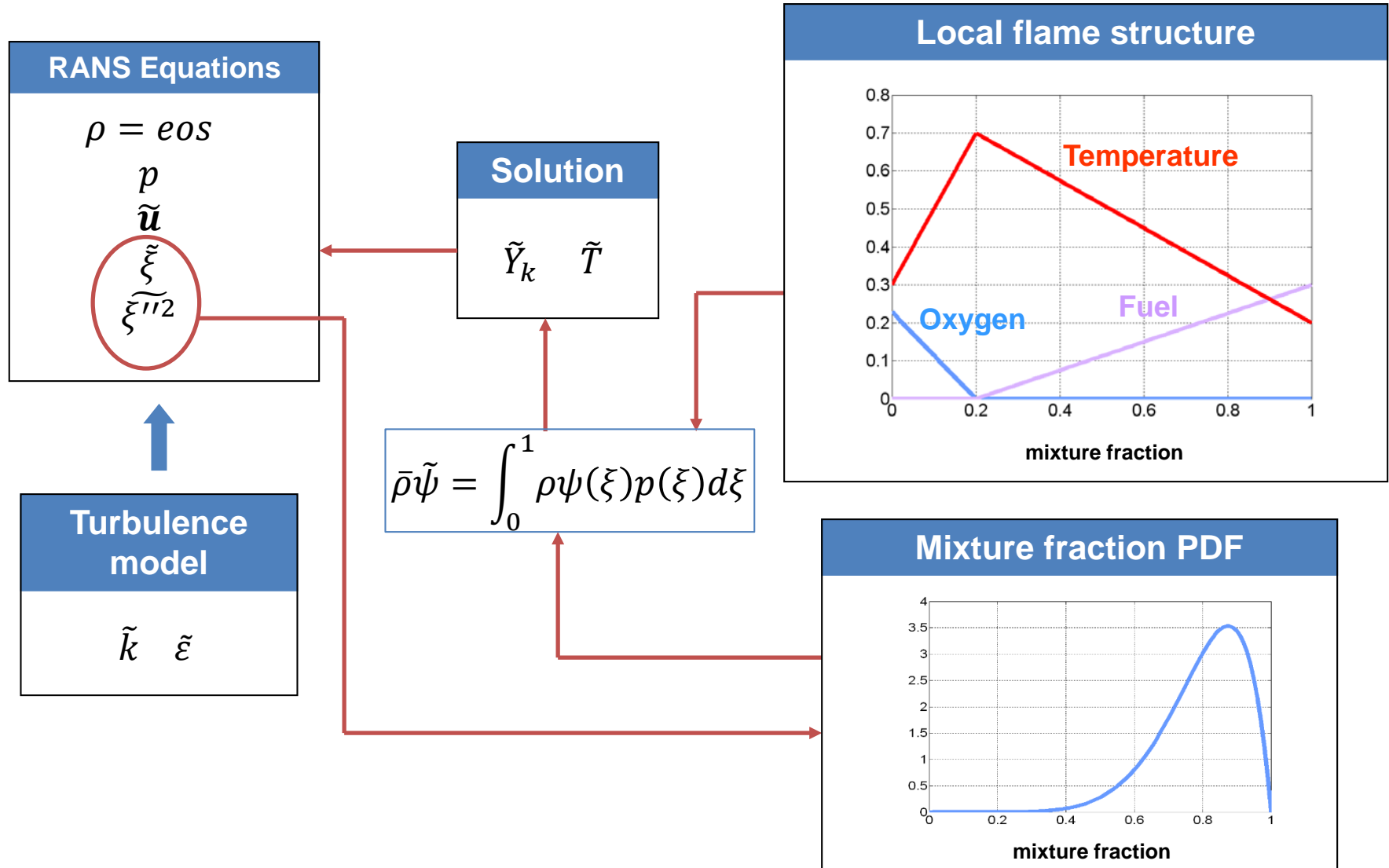


**Variance of
Mixture
fraction**

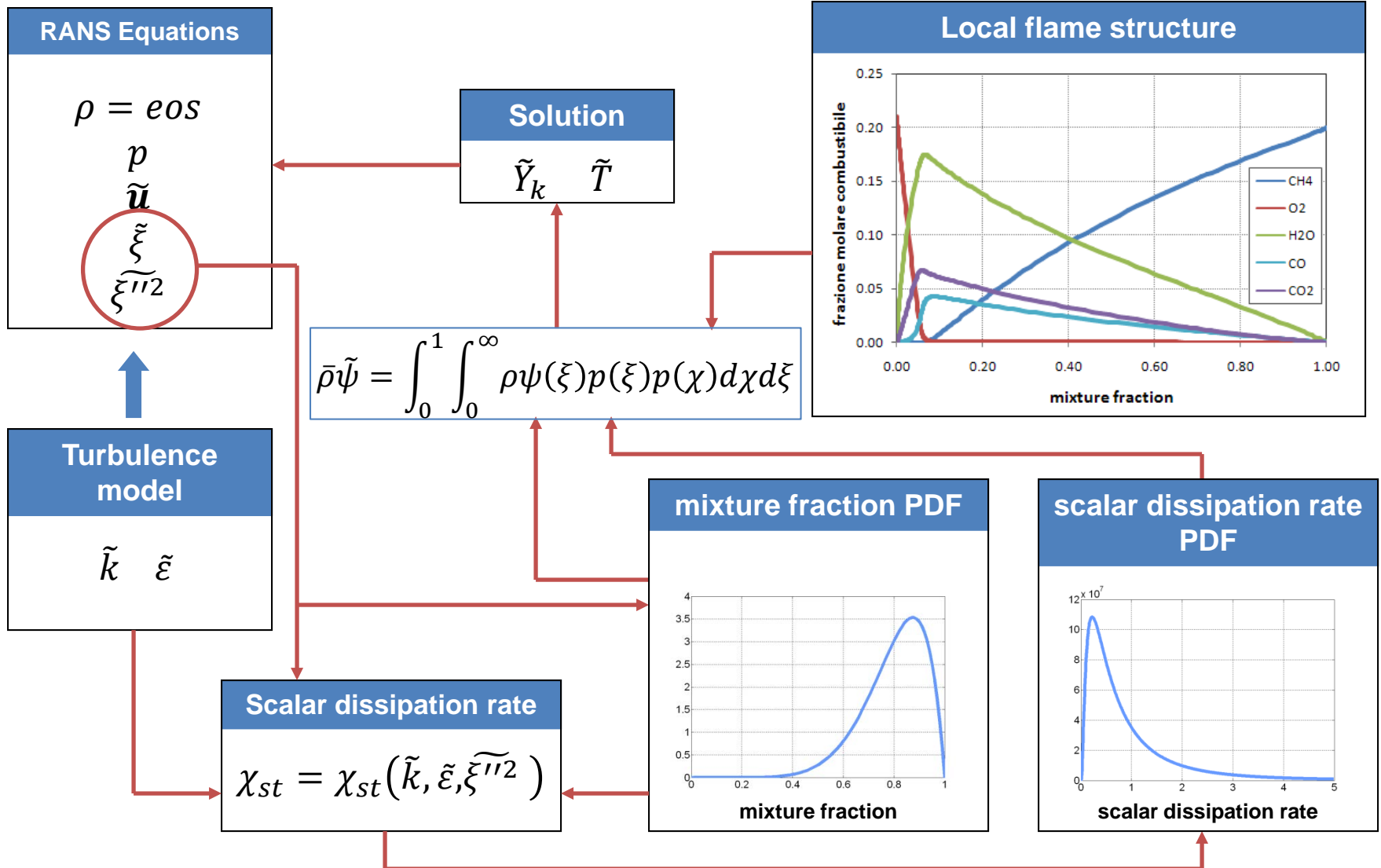
**Mixture fraction
(mean value)**

**Scalar
Dissipation Rate**

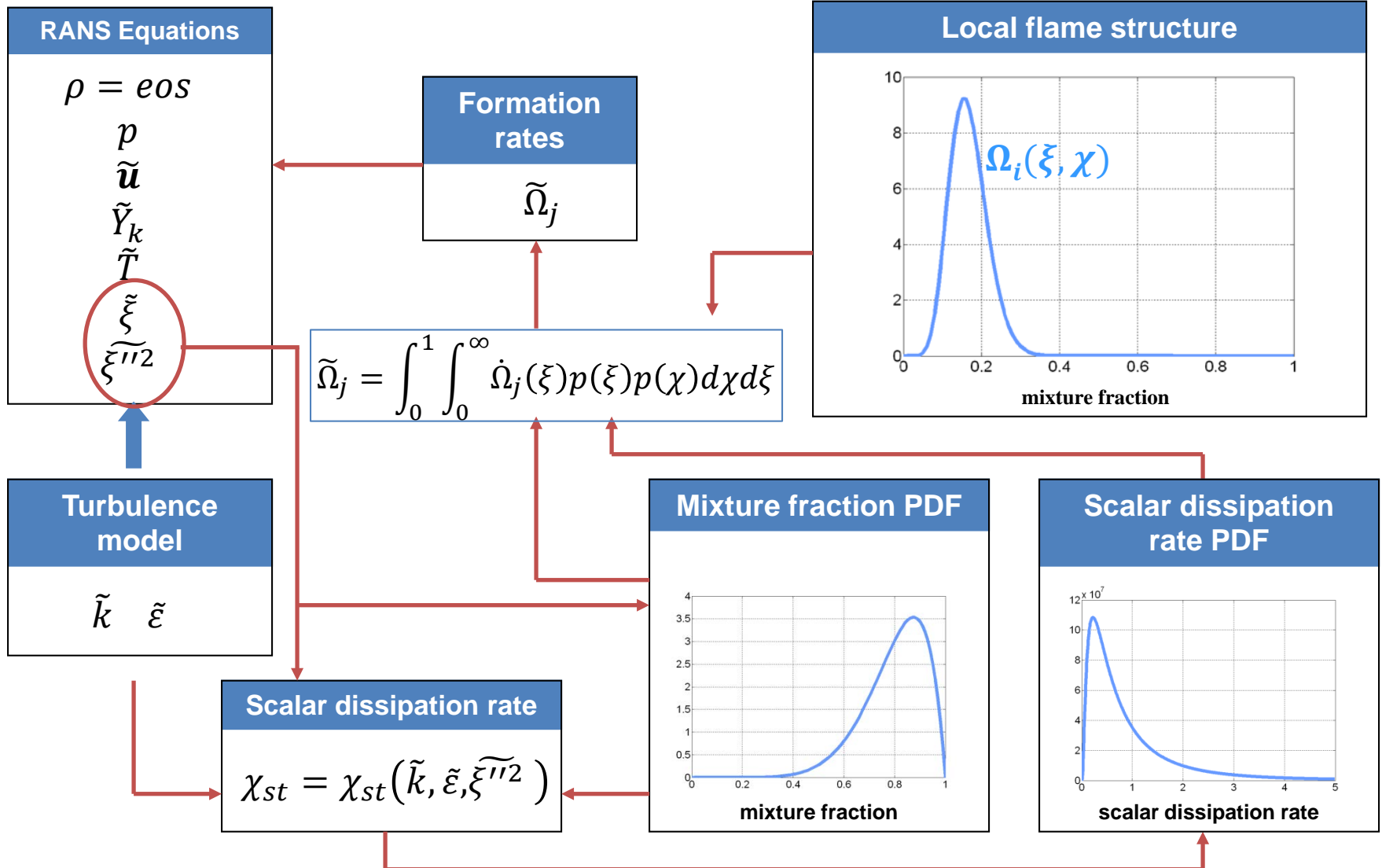
Infinitely Fast Chemistry



Finite Rate Chemistry



Reaction Rate - Flamelets



Final remarks on flamelet model

- A **large variety of flamelet approaches** exist and have been successfully applied to various configurations.
- Flamelet models are particularly adapted to LES, which provides good prediction of the filtered and subgrid variables, as well as their time evolution, to be used in the flamelet library.
- One important feature of flamelet methods is that they give **access to the fully detailed chemical structure of the flame, including all minor species**.
- **Optimized and efficient tabulation techniques (e.g. ILDM, ISAT, FPI)** enable the use of flamelet libraries in complex flow simulations. This is of major importance to predict pollutant emissions and soot.
- Flamelet models are still being developed, in particular to account for heat losses or liquid fuel sprays or to predict diesel engine auto-ignition.
- Although a large majority of industrial systems are fed with separate fuel and oxidizer flows, the flame in the chamber is usually partially-premixed, with premixed and non-premixed flame elements. In this case **unified models adapted to both premixed and diffusion flames** must be developed. Flamelet methods are good candidates, as they are able to involve both the mixture fraction and the progress variable.

Training Session 5 (optional)

Numerical simulation of Sandia CO/H₂/N₂ turbulent Jet Flames.

The test case is a CO/H₂/N₂ non-premixed, unconfined, turbulent jet flame. The fuel is injected from a straight circular tubing with squared-off ends (inner diameter 4.58 mm, outer diameter 6.34 mm) at 76 m/s and the corresponding Reynolds number is 16700. The air coflows at 0.75 m/s. The syngas percent composition is 40/30/30 in volume. The fuel tubing length is sufficient to make the assumption of fully developed turbulent pipe flow appropriate. Detailed description of operating conditions and experimental data are available at <https://www.sandia.gov/TNF/DataArch/SANDchn.html>

The simulations are carried out using the flameletSMOKE code, freely available at the following GitHub address: <https://github.com/acuoci/flameletSMOKE>

Detailed instructions on how to compile and install flameletSMOKE are reported in the associated README file:

<https://github.com/acuoci/flameletSMOKE/blob/master/README.md>

Detailed instructions on how to setup and run the H₂/N₂ flames are available here:

<https://github.com/acuoci/flameletSMOKE/tree/master/cases>

1. Introduction to turbulent combustion modeling

- a) Fluid dynamic and chemical time scales
- b) Effects of turbulent fluctuations on chemical reactions
- c) Need of turbulent combustion models

2. Non-premixed combustion

- a) Eddy Dissipation models: ED, ED-FR, EDC
- b) Steady Laminar Flamelet model
 - i. Mixture fraction
 - ii. Flamelet equations
 - iii. Presumed PDF approach

3. Premixed combustion

- a) Eddy Break-Up (EBU) model
- b) Bray-Libby-Moss (BLM) model
- c) G-Equation

Eddy Break-Up Model (I)

- Proposed by Spalding, the Eddy Break Up (EBU) model is based on a phenomenological analysis of turbulent combustion assuming **high Reynolds ($Re \gg 1$) and Damkohler ($Da \gg 1$) numbers**.
- A simple idea is to consider that **chemistry does not play any explicit role** while turbulent motions control the reaction rate
- The reaction zone is viewed as a collection of fresh and burnt gaseous pockets transported by turbulent eddies
- The mean reaction rate is mainly controlled by a **characteristic turbulent mixing time τ_t** and the normalized temperature (or product mass fraction) fluctuations θ and is expressed as:

$$\bar{r} = C_{EBU} \bar{\rho} \frac{\sqrt{\overline{\theta'^2}}}{\tau_t}$$

C_{EBU} is a model constant of the order of unity. The turbulence time τ_t can be interpreted as the rate of turbulent mixing between reactants and products and is estimated as:

$$\tau_t = \tilde{k} / \tilde{\varepsilon}$$

Eddy Break-Up Model (II)

The EBU Model requires the estimation of fluctuations $\widetilde{\theta''^2}$. In case θ is chosen as the normalized temperature, a first analysis assuming that the flame is infinitely thin leads to the simple result:

$$\bar{\rho}\widetilde{\theta''^2} = \overline{\rho(\theta - \tilde{\theta})^2} = \bar{\rho}(\widetilde{\theta^2} - \tilde{\theta}^2) = \bar{\rho}\tilde{\theta}(1 - \tilde{\theta})$$

because the normalized temperature can only take two values, $\theta = 0$ (in the fresh gases) or $\theta = 1$ (in the fully burnt gases) so that $\theta^2 = \theta$. The final EBU model for the mean reaction rate is:

$$\bar{r} = C_{EBU}\bar{\rho}\frac{\tilde{\varepsilon}}{\tilde{k}}\tilde{\theta}(1 - \tilde{\theta})$$

- This model is attractive because the reaction rate is written as a simple function of known mean quantities without additional transport equations.
- Despite its success, its basic form has an obvious limitation: it does not include any effects of chemical kinetics. However, the EBU model generally gives better results than the simple Arrhenius model.

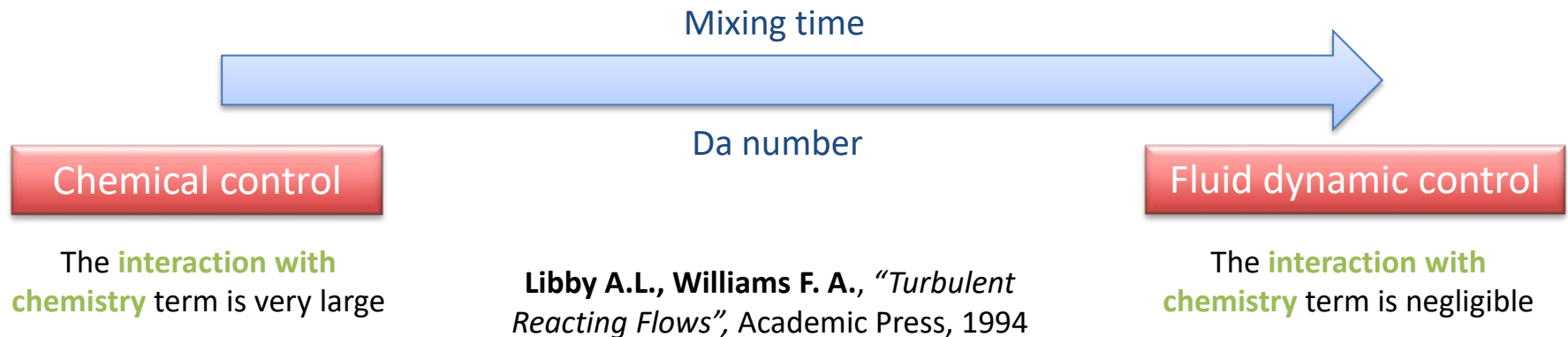
Eddy Break-Up Model (III)

Some adjustments have been proposed to incorporate chemical features. Libby and Williams proposed a more advanced model in which θ is the fuel mass fraction. The fluctuations are estimated on the basis of a transport equation:

$$\bar{\rho} \frac{\partial \overline{\theta''^2}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \overline{\theta''^2}}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\bar{\rho} \frac{\mathcal{D}_t}{Sc_t} \frac{\partial \overline{\theta''^2}}{\partial x_i} \right) + \bar{S}_{\overline{\theta''^2}}$$

The source term is given by the sum of three contributions:

$$\bar{S}_{\overline{\theta''^2}} = \underbrace{\bar{P}_{\overline{\theta''^2}}}_{\text{production}} + \underbrace{\bar{D}_{\overline{\theta''^2}}}_{\text{dissipation}} + \underbrace{\bar{K}_{\overline{\theta''^2}}}_{\text{interaction with chemistry}}$$



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- c) G-Equation

Bray-Libby-Moss (BLM) Model (I)

Flamelet concept for premixed turbulent combustion: Bray-Moss-Libby-Model (BML)

The formulation is based on a reaction progress variable equal to 0 in unburned reactants (u), rising monotonically to a value of 1 in fully-burned products (b).

The reaction progress variable can be related to a particular species mass fraction, for a specific product Y_p or for the fuel itself Y_f :

$$c = \frac{Y_p}{Y_{p,b}} \quad or \quad c = \frac{Y_f - Y_{f,u}}{Y_{f,b} - Y_{f,u}}$$

For adiabatic flames with Lewis number equal to 1 it is possible to adopt a definition directly based on the temperature:

$$c = \frac{T - T_u}{T_b - T_u}$$

Bray-Libby-Moss (BLM) Model (II)

Favre averaged transport equation:

$$\bar{\rho} \frac{\partial c}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial c}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\overline{\rho \mathcal{D}_c} \frac{\partial c}{\partial x_i} \right) - \frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' c''}) + \bar{S}_c$$

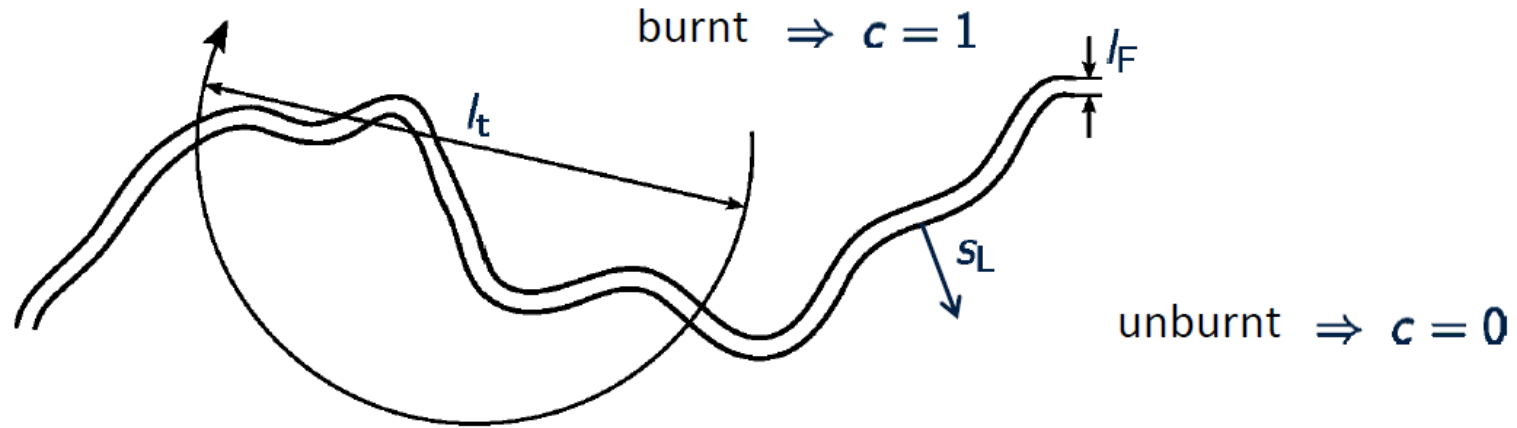
The terms on the right hand side are unclosed. Typically, the molecular transport is neglected. On the contrary, closure models for the turbulent transport and chemical source terms are required:

$$\bar{\rho} \frac{\partial c}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial c}{\partial x_i} = \underbrace{-\frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' c''})}_{\text{turbulent transport}} + \underbrace{\bar{S}_c}_{\text{source}}$$

Unclosed terms

Bray-Libby-Moss (BLM) Model (III)

Assumption: very fast chemistry, flame size $l_F \ll \eta \ll l_t$



Specification of a PDF (probability distribution function) for the progress variable:

- the turbulent flame is made up of thin flamelets
- a probe inserted into the flame brush at a fixed location in space will detect reactants for some of the time and products for almost all the rest of the time
- since the flamelet interface is thin, the probe will detect reacting gases only for very short intervals

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Bray-Libby-Moss (BLM) Model (IV)

Simplification: progress variable is expected solely to be $c = 0$ (unburnt) or $c = 1$ (burnt)

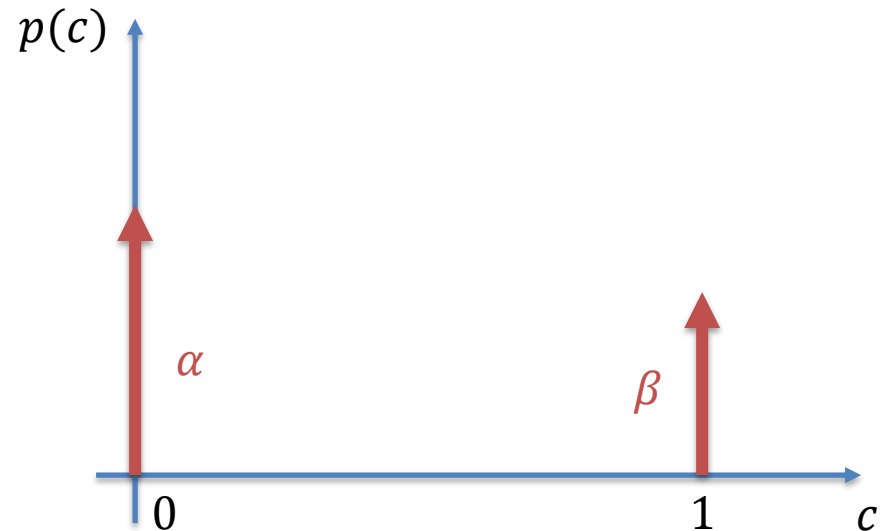
Probability density function:

$$p(c) = \alpha\delta(c) + \beta\delta(c - 1)$$

α and β are the probabilities to encounter the unburnt or the burnt mixture in the flow field

No intermediate states are allowed, which means that $\alpha + \beta = 1$

δ is the Dirac delta function



$$\delta(c) = \begin{cases} \infty & \text{if } c = 0 \\ 0 & \text{elsewhere} \end{cases} \quad \int_{-\infty}^{+\infty} g(c)\delta(c - c_0) = g(c_0)$$

Bray-Libby-Moss (BLM) Model (V)

For a Favre average:

$$\bar{\rho} \tilde{Q} = \int_0^1 \int_{-\infty}^{+\infty} \rho Q(u, c) p_{\mathbf{u}, c}(\mathbf{u}, c) d\mathbf{u} dc$$

Therefore, the unclosed correlation $\widetilde{u_i'' c''}$ can be calculated on the basis of the joint pdf for \mathbf{u} and c :

$$p_{\mathbf{u}, c}(\mathbf{u}, c) = p_c(c) p_{\mathbf{u}|c}(\mathbf{u}|c)$$

Introducing the BML approach for $p_c(c)$ leads to:

$$p_{\mathbf{u}, c}(\mathbf{u}, c) = \alpha \delta(c) \underbrace{p_{\mathbf{u}|c}(\mathbf{u}|c = 0)}_{\text{conditional pdf}} + \beta \delta(c - 1) p_{\mathbf{u}|c}(\mathbf{u}|c = 1)$$

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Bray-Libby-Moss (BLM) Model (VI)

$$\bar{\rho}\tilde{Q} = \int_0^1 \int_{-\infty}^{+\infty} \rho Q(u, c) p_{\mathbf{u},c}(\mathbf{u}, c) d\mathbf{u} dc$$

$$\begin{aligned} \bar{\rho} \widetilde{u_i'' c''} &= \int_0^1 \int_{u_{i,min}}^{u_{i,max}} \rho (u_i - \tilde{u}_i) (c - \tilde{c}) p_{\mathbf{u},c}(\mathbf{u}, c) d\mathbf{u} dc = \dots \\ &\dots = \bar{\rho} \tilde{c} (1 - \tilde{c}) (\bar{u}_b - \bar{u}_u) \end{aligned}$$

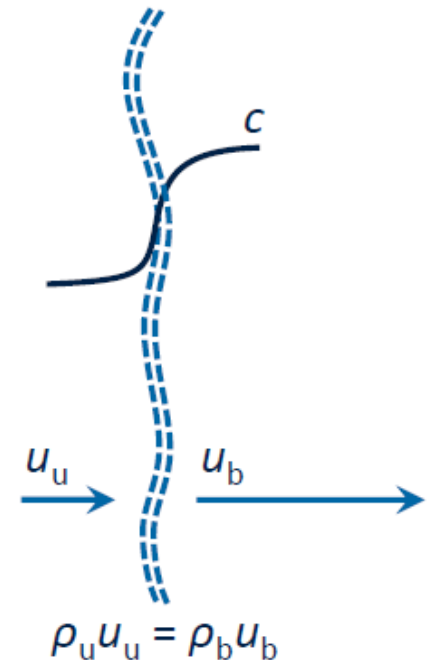
Since the density of products (i.e. burnt mixture) is much smaller than density of reactants, we have:

$$\bar{u}_b - \bar{u}_u > 0$$

Since the progress variable is by definition is $0 \leq c \leq 1$, at the end we have:

$$\widetilde{u_i'' c''} = \bar{\rho} \tilde{c} (1 - \tilde{c}) (\bar{u}_b - \bar{u}_u) \geq 0$$

Flame front



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Bray-Libby-Moss (BLM) Model (VII)

Within the flame zone the progress variable, by definition, increases, i.e.:

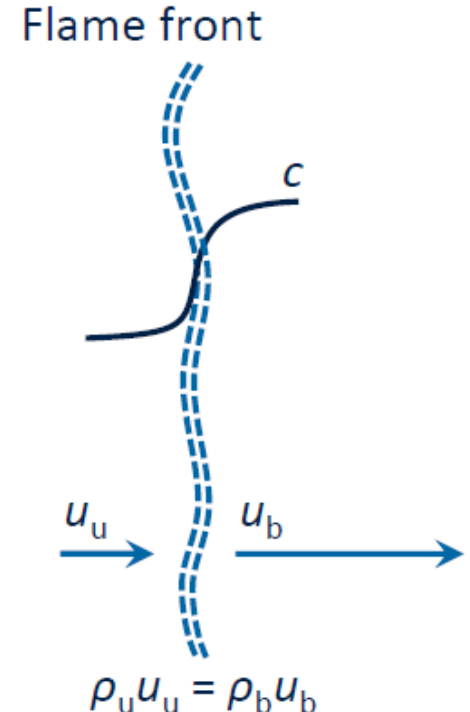
$$\frac{\partial \tilde{c}}{\partial x_i} \geq 0$$

Gradient transport model would be:

$$\widetilde{u_i'' c''} = -\mathcal{D}_t \frac{\partial \tilde{c}}{\partial x_i} \leq$$

This is in conflict with the previous result:

$$\widetilde{u_i'' c''} = \bar{\rho} \tilde{c} (1 - \tilde{c}) (\bar{u}_b - \bar{u}_u) \geq 0$$



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Flame Surface Density model

- Closure by BML-model $p(c)$ leads to $\bar{S}_c = 0$
- Closure of the chemical source term, e.g. by **flame-surface-density-model**:

$$\bar{S}_c = \rho_u s_L^0 l_0 \Sigma$$

local mass conversion per area

flame-surface-density

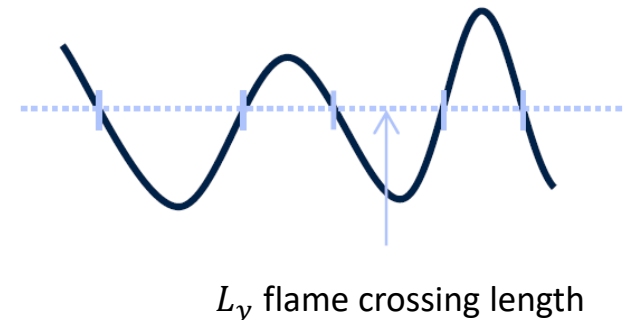
l_0 : strain factor, i.e. a measure of local increase of burning velocity by strain

Σ : Flame-surface-density

- algebraic model:

$$\Sigma \sim \frac{\tilde{c}(1 - \tilde{c})}{L_y}$$

- transport equation for Σ



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Transport equation for Σ

$$\frac{\partial \Sigma}{\partial t} + \frac{\partial \tilde{u}_i \Sigma}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\mathcal{D}_t \frac{\partial \Sigma}{\partial x_i} \right) + \underbrace{C_1 \frac{\varepsilon}{k} \Sigma}_{\text{production due to stretching of the flame}} - \underbrace{C_2 s_L \frac{\Sigma^2}{1 - \tilde{c}}}_{\text{Flame annihilation}}$$

No chemical time scales

- Turbulent time ($\tau = k/\varepsilon$) is the determining time scale
- Limit of **infinitely fast chemistry**
- By using transport equations \rightarrow model for chemical source term independent of s_L

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- c) **G-Equation**

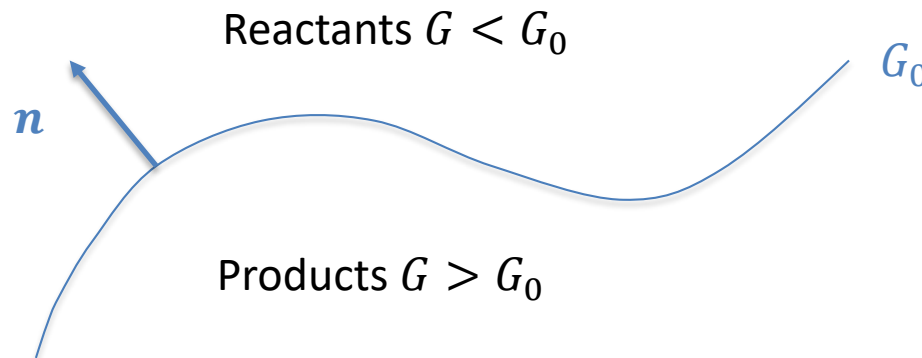
The G-Equation

The G-Equation is widely used for turbulent combustion modeling and it has proved especially useful as a basis for sub-grid modelling for LES

There are strong similarities with the FSD approach, but there are significant differences too and the G-equation offers a greater degree of flexibility in modeling

The formulation makes use of a non-reacting variable denoted by G

The flame surface is represented by a level set (i.e. iso-surface) of the scalar at $G(x, t) = G_0$, where G_0 is an arbitrary fixed value (typically chosen as zero)



The flame normal vector is defined by

$$\mathbf{n} = -\frac{\nabla G}{|\nabla G|}$$

And points into the reactants

The G-Equation

The propagation of the surface $G = G_0$ is described by the kinematic equation:

$$\frac{\partial \mathbf{x}_F}{\partial t} = \mathbf{u} + s_L \mathbf{n}$$

where \mathbf{u} is the flow velocity at the surface $G = G_0$ that is located instantaneously at \mathbf{x}_F and s_L is the displacement speed of the surface relative to the underlying fluid.

Then, using the expansion:

$$\frac{\partial G}{\partial t} + \nabla G \cdot \frac{\partial \mathbf{x}_F}{\partial t} = 0$$

We get the final G-equation:

$$\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = s_L |\nabla G|$$

Local change convection Progress of flame front by burning velocity

The G-Equation

$$\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = s_L |\nabla G|$$

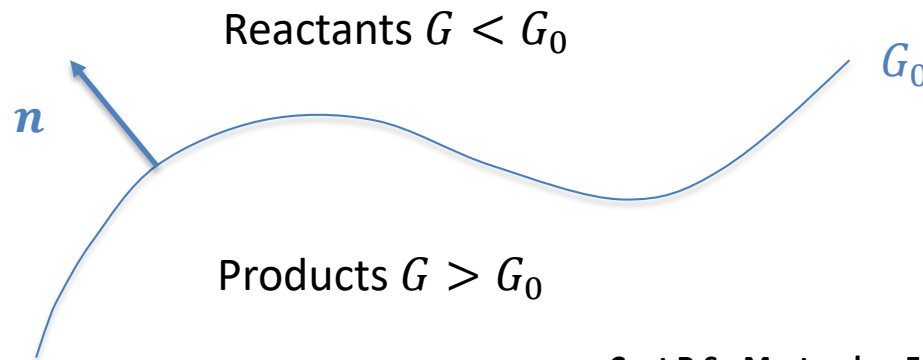
- The G-equation contains no diffusion and no reaction terms
- The quantity G is a field variable in three-dimensional space while the level set $G=G_0$ defines a two-dimensional surface within that field
- The application to premixed flames depends only on the description of the propagation of the surface at $G=G_0$, and in principle the rest of the G field can remain arbitrary
- The G-Equation model can be applied for thin flames and well-defined burning velocities, i.e. in the regime of corrugated flamelets

Cant R.S., Mastorakos E. *"An Introduction to Turbulent Reacting Flows"*, Imperial College Press 2008

$$\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = s_L |\nabla G|$$

- This is a kinematic equation, i.e. the density does not appear in the equation
- Valid for flame position: $G = G_0$
 - For solving the field equation, G needs to be defined in the entire field
 - Different possibilities to define G , e.g. signed distance function:

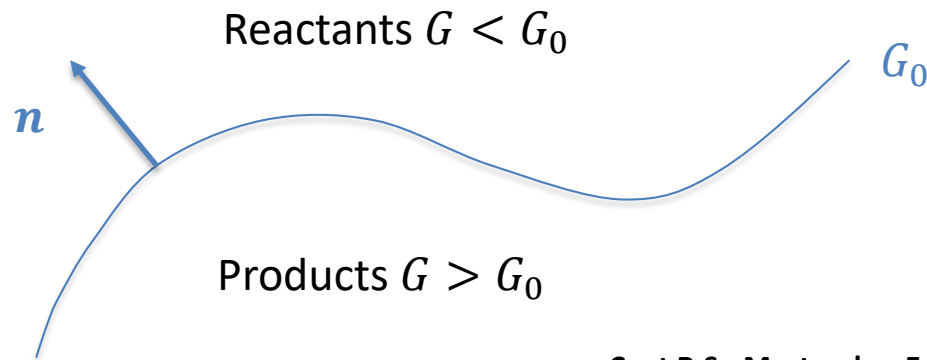
$$|\nabla G| = 1$$



Cant R.S., Mastorakos E. "An Introduction to Turbulent Reacting Flows", Imperial College Press 2008

$$\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = s_L |\nabla G|$$

- Influence of chemistry by s_L
- s_L is not necessarily constant, but it is influenced by
 - Strain S
 - Curvature K
 - Lewis number
- Modified laminar burning velocity



Cant R.S., Mastorakos E. "An Introduction to Turbulent Reacting Flows", Imperial College Press 2008

Laminar burning velocity: curvature

Curvature $\kappa = \frac{\partial n_i}{\partial x_i} = \frac{\partial}{\partial x_i} \left(-\frac{\frac{\partial G}{\partial x_i}}{|\nabla G|} \right)$

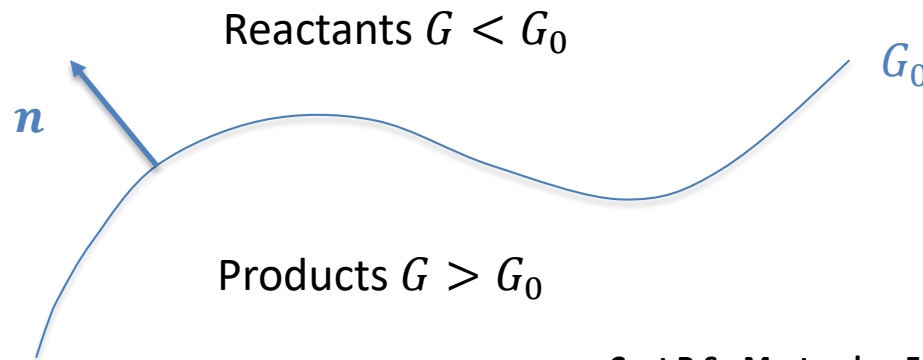
Is the curvature of the surface at $G = G_0$ expressed simply as the divergence of the local normal vector

Influence of curvature

$$s_L = s_L^0 - s_L^0 \mathcal{L} \kappa - \mathcal{L} S$$

\mathcal{L} is a Markstein length, expected to be $\sim \delta_L$

This is a linear model for the dependence of the burning velocity on the curvature



Cant R.S., Mastorakos E. "An Introduction to Turbulent Reacting Flows", Imperial College Press 2008

Laminar burning velocity: Markstein length

$$s_L = s_L^0 - s_L^0 \mathcal{L} \kappa - \mathcal{L} S$$

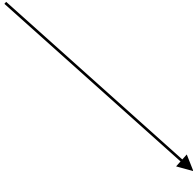
\mathcal{L} is a Markstein length, expected to be of the same order of the laminar flame thickness, i.e. $\mathcal{L} \sim \delta_L$

The Markstein length can be:

- Determined by experiments
- Determined by asymptotic analyses

$$\mathcal{L} = \mathcal{M} \delta_L$$

The larger the Markstein length, the greater the effect of curvature on localized burning velocity.



the Markstein number \mathcal{M} characterizes the effect of local heat release of a propagating flame on variations in the surface topology along the flame and the associated local flame front curvature

Laminar burning velocity: curvature

Strain rate

$$\mathcal{S} = -n_i \frac{\partial u_i}{\partial x_j} n_j$$

S is the strain rate in the plane of the surface. It is equal to the tangential strain rate provided that the velocity divergence is zero, i.e. in the absence of compressibility or heat release effects

Influence of strain rate

$$s_L = s_L^0 - s_L^0 \mathcal{L} \kappa - \mathcal{L} \mathcal{S}$$

\mathcal{L} is a Markstein length, expected to be $\sim \delta_L$

This is a linear model for the dependence of the burning velocity on the strain rate

Incorporating the expression above in the G-equation, we have the following modified G-equation:

$$\frac{\partial G}{\partial t} + u_i \frac{\partial G}{\partial x_i} = (s_L^0 - s_L^0 \mathcal{L} \kappa - \mathcal{L} \mathcal{S}) |\nabla G|$$

Cant R.S., Mastorakos E. "An Introduction to Turbulent Reacting Flows", Imperial College Press 2008

Turbulent premixed flames with G

In a turbulent flow field it is helpful to assume that G is both well-defined and well-behaved outside the surface at $G = G_0$. Then it is possible to define the PDF of G denoted by $p(G; \mathbf{x}, t)$.

The mean and the variance of G are given by the integration over the pdf as:

$$\bar{G} = \int G p(G; \mathbf{x}, t) dG$$

$$\overline{G'^2} = \int (G - \bar{G})^2 p(G; \mathbf{x}, t) dG$$

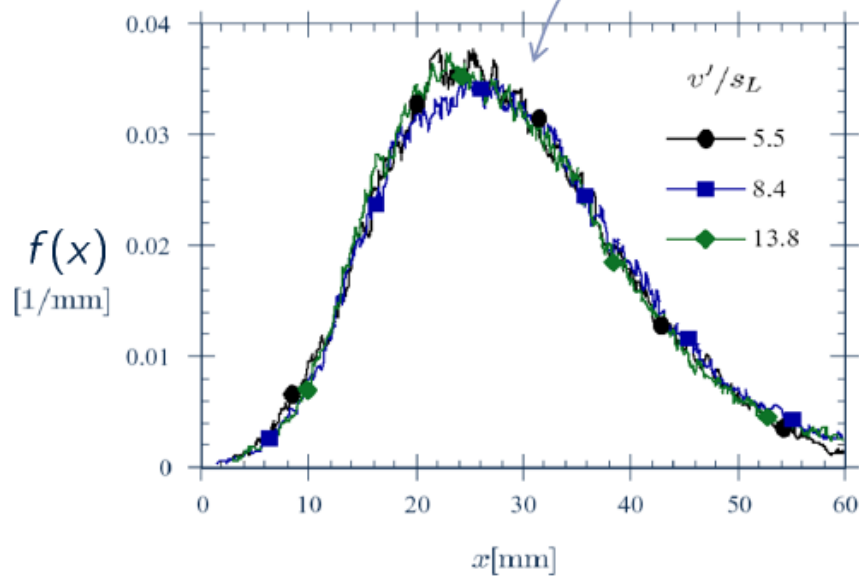
It would be straightforward to derive balance equations for these quantities, which could be modelled and solved.

Instead it is more interesting to consider further the relationship between G and the distance field.

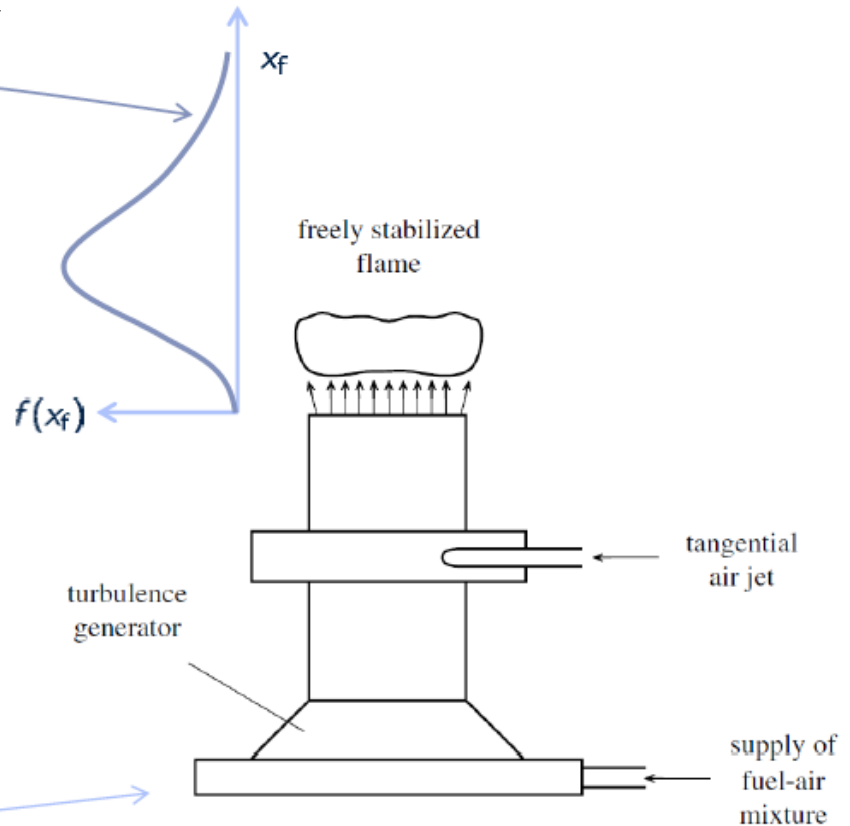
Statistical description of turbulent flame front (I)

Probability Density Function of finding $G = G_0$

$$p(G_0; \mathbf{x}, t) = \int \delta(G - G_0) p(G; \mathbf{x}, t) dG$$



Experimental determination
in weak swirl burner



Pitsch H., "Combustion Theory and Applications in CFD", Princeton Combustion Summer School 2018

Statistical description of turbulent flame front (II)

The PDF of finding the surface $G = G_0$ at an arbitrary spatial location \mathbf{x} at time t may be stated as:

$$p(G_0; \mathbf{x}, t) = \int \delta(G - G_0) p(G; \mathbf{x}, t) dG$$

It is clear that this PDF provides information about the statistical geometry or spatial distribution of the flame surface, similarly to that provided by the BML flame cross frequency and the FSD approach.

Let us now focus on the ideal case of a locally 1D statistically stationary turbulent flame (see previous slide). All the quantities can be considered as functions of a single spatial coordinate x .

Then, the mean and variance of the flame position x_F are given by:

$$x_F = \int x p(G_0; x, t) dx$$

$$\overline{(x - x_F)^2} = \int (x - x_F)^2 p(G_0; x, t) dx$$

Statistical description of turbulent flame front (III)

The variance of the flame position can be also interpreted as the squared flame brush thickness, i.e.:

$$l_f = \sqrt{(x - x_F)^2}$$

It is helpful to relate the mean and variance of flame position more closely to the mean and variance of G :

$$\bar{G}(x) - G_0 = x - x_F$$

Which means that the mean flame position $x = x_F$ is fixed at the location where $\bar{G} = G_0$.

Fluctuations of G about the mean are given by:

$$G' = G - \bar{G} = G - (G_0 + x - x_F)$$

Setting $G = G_0$ at the surface provides:

$$G' = -(x - x_F)$$

Statistical description of turbulent flame front (IV)

Thus, the scalar variable G can be interpreted as the scalar distance between the instantaneous and the mean flame positions, measured in the direction normal to the mean turbulent brush.

The analysis we carried out was limited to 1D cases. However, it can be extended to more general 2D and 3D cases. The mean flame location can be defined by $G(x, t) = G_0$ and by the expression for the normal distance:

$$x = x_F + \frac{\bar{G} - G_0}{|\nabla G|}$$

Note that the re-initialization condition $|\nabla G| = 1$ must be applied in order to guarantee the regularity of the G field away from the mean flame location.

Cant R.S., Mastorakos E. *“An Introduction to Turbulent Reacting Flows”*, Imperial College Press 2008

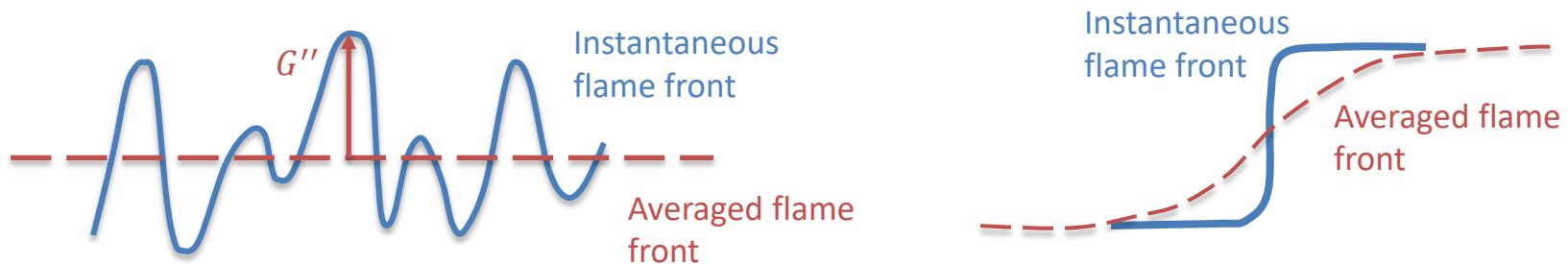
Favre Mean and Variance Equations

Using Favre averaging it is possible to derive equation for the Favre averaged mean and variance of G:

$$\bar{\rho} \frac{\partial \tilde{G}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \tilde{G}}{\partial x_i} = \overline{(\rho s_L^0) \sigma} - \overline{(\rho \mathcal{D}) \kappa \sigma} - \frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' G''})$$

$$\bar{\rho} \frac{\partial \widetilde{G''^2}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \widetilde{G''^2}}{\partial x_i} + \frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' G''^2}) = -2 \bar{\rho} \widetilde{u_i'' G''} \frac{\partial \tilde{G}}{\partial x_i} - \bar{\rho} \tilde{\omega} - \bar{\rho} \tilde{\chi} - (\rho \mathcal{D}) \overline{\kappa \sigma}$$

- $\sigma \stackrel{\text{def}}{=} |\nabla G|$ can be interpreted as the area ratio of the flame A_T/A
- As already mentioned, the variance describes the average size of the flame



Sink terms in the variance equation

$$\bar{\rho} \frac{\partial \widetilde{G''^2}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \widetilde{G''^2}}{\partial x_i} + \frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' G''^2}) = -2 \bar{\rho} \widetilde{u_i'' G''} \frac{\partial \tilde{G}}{\partial x_i} - \bar{\rho} \tilde{\omega} - \bar{\rho} \tilde{\chi} - (\rho \mathcal{D}) \overline{\kappa \sigma}$$

Kinematic restoration

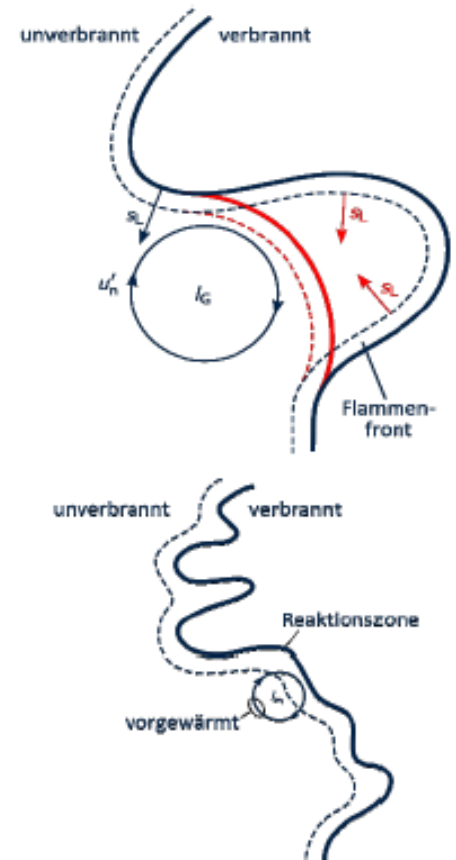
$$\tilde{\omega} = -2(\rho s_L^0) \frac{\overline{G'' \sigma}}{\bar{\rho}}$$

Scalar dissipation

$$\tilde{\chi} = 2 \frac{\overline{\rho \mathcal{D}}}{\bar{\rho}} \left(\frac{\partial \widetilde{G''}}{\partial x_i} \right)^2$$

They are typically modelled as:

$$\tilde{\omega} + \tilde{\chi} = C_s \frac{\tilde{\varepsilon}}{\tilde{k}} \widetilde{G''^2}$$



Pitsch H., "Combustion Theory and Applications in CFD", Princeton Combustion Summer School 2018

Turbulent burning velocity (I)

Turbulent transport is commonly treated using a gradient transport model:

$$\bar{\rho} \widetilde{u_i'' G''} = -\bar{\rho} \mathcal{D}_t \frac{\partial \tilde{G}}{\partial x_i}$$

However, this would introduce a 2nd order derivative of G, changing the mathematical character of the G equation. Instead, the modelled gradient diffusion term may be decomposed into normal and tangential components:

$$\nabla \cdot (\bar{\rho} \mathcal{D}_t \nabla \tilde{G}) = n \cdot \nabla (\bar{\rho} \mathcal{D}_t n \cdot \nabla \tilde{G}) - \bar{\rho} \mathcal{D}_t \tilde{\kappa} |\nabla \tilde{G}|$$

Thus, after neglecting the molecular diffusion contribution, the sum of RHS terms in the G equation can be rewritten as:

$$\overline{(\rho s_L^0) |\nabla G|} - \nabla \cdot (\bar{\rho} \widetilde{u'' G''}) = [\overline{(\rho s_L^0) |\nabla G|} + n \cdot \nabla (\bar{\rho} \mathcal{D}_t n \cdot \nabla \tilde{G})] - \bar{\rho} \mathcal{D}_t \tilde{\kappa} |\nabla \tilde{G}|$$

The term in the square brackets is written introducing the turbulent burning velocity:

$$(\rho s_T^0) |\nabla \tilde{G}| \stackrel{\text{def}}{=} \overline{(\rho s_L^0) |\nabla G|} + n \cdot \nabla (\bar{\rho} \mathcal{D}_t n \cdot \nabla \tilde{G})$$

Turbulent burning velocity (II)

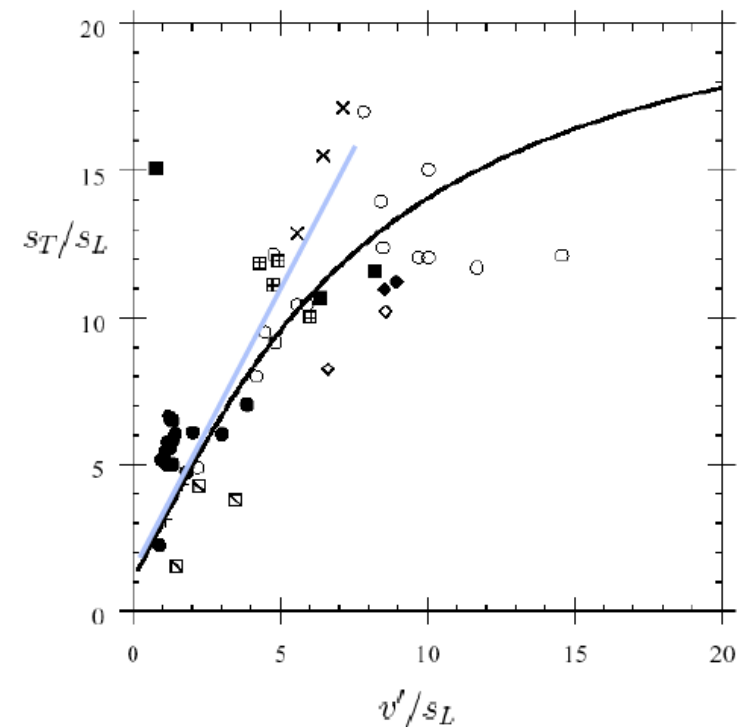
Introducing the turbulent burning velocity s_T^0 :

$$(\rho s_T^0) |\nabla \tilde{G}| \stackrel{\text{def}}{=} \overline{(\rho s_L^0) |\nabla G|} + n \cdot \nabla (\bar{\rho} \mathcal{D}_t n \cdot \nabla \tilde{G})$$

Example: modeling of turbulent burning velocity by the Damkohler theory:

$$\frac{s_T^0}{s_L^0} = 1 - \alpha \frac{l_t}{l_F} + \sqrt{\left(\alpha \frac{l_t}{l_F}\right)^2 + 4\alpha \frac{u' l_t}{s_L l_F}}$$

It is interesting to note that the turbulent burning velocity appears as an input to the Favre averaged G-equation formulation and it is not part of the solution



Pitsch H., "Combustion Theory and Applications in CFD", Princeton Combustion Summer School 2018

Favre Mean and Variance Equations

Equation for the Favre mean

$$\bar{\rho} \frac{\partial \tilde{G}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \tilde{G}}{\partial x_i} = (\rho s_T^0) |\nabla \tilde{G}| - \bar{\rho} \mathcal{D}_t \tilde{\kappa} |\nabla \tilde{G}|$$

Equation for variance

$$\bar{\rho} \frac{\partial \widetilde{G''^2}}{\partial t} + \bar{\rho} \tilde{u}_i \frac{\partial \widetilde{G''^2}}{\partial x_i} = \nabla_{||} \cdot (\bar{\rho} \mathcal{D}_t \nabla_{||} \widetilde{G''^2}) - 2 \bar{\rho} \mathcal{D}_t \left(\frac{\partial \tilde{G}}{\partial x_i} \right)^2 - \bar{\rho} C_s \frac{\tilde{\varepsilon}}{\tilde{k}} \widetilde{G''^2}$$

Similar arguments
have been applied to
the closure of the
turbulent transport
term $\frac{\partial}{\partial x_i} (\bar{\rho} \widetilde{u_i'' G''^2})$

Presumed PDF approach

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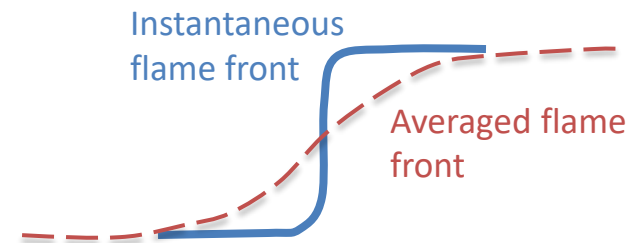
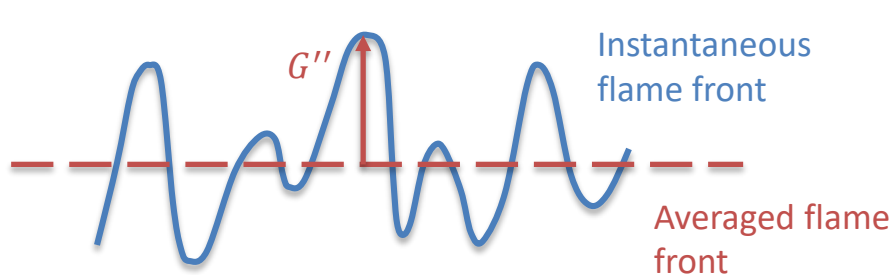
Typically a Gaussian Distribution is assumed

$$p(G; x, t) = \frac{1}{\sqrt{2\pi\widetilde{G''^2}|_0}} \exp\left(-\frac{(G - \tilde{G})^2}{2\widetilde{G''^2}|_0}\right)$$

Mean temperature (and other scalars)

$$\tilde{T}(x, t) = \int T(G) p(G; x, t) dG$$

$T(G)$ is taken from the laminar premixed flame without strain



Other methods: tabulation of chemistry (I)

- In general, turbulent premixed flames well away from extinction can be modelled without explicit consideration of the chemical reaction rate. Chemical information is encapsulated in quantities such as the **laminar burning velocity** and its response to straining.
- The computational costs of detailed chemistry are high, and it is preferable to treat the chemistry separately from any turbulent flame calculation. This is true especially in LES where computational costs are already high due to the demand for fine spatial resolution and the need for unsteady solutions.
- **Chemistry can be precomputed and stored in tabulated form** using a number of different approaches. Perhaps the simplest is a **premixed flamelet library**, in which the laminar burning velocity can be stored as a function of mixture strength, pressure and reactant temperature.
- Other independent variables can be included, such as strain rate and mean curvature. In order to avoid the computational costs of searching in tables, it is possible to make use of correlations for laminar burning velocity which have been derived from either experimental or one-dimensional computations .

Other methods: tabulation of chemistry (II)

An approach such as Flamelet Generated Manifolds (FGM) or Flamelet Prolongation of ILDM (FPI) allows for a reasonable level of chemical detail that is computationally inexpensive - at least within the turbulent flame calculation - and which is largely free from the restrictions of the original flamelet concept.

Gicquel, O., Darabiha, N., Thevenin, D., Laminar premixed hydrogen/air counterflow flame simulations using flame prolongation of ILDM with preferential diffusion. *Proc. Combust. Inst.* 28, 1901–1908 (2000)

van Oijen, J.A., de Goey, L.P.H., Modelling of premixed laminar flames using flamelet generated manifolds. *Combust. Sci. Technol.* 161, 113–138 (2000)

Other methods: Transported PDF

- The transported pdf approach makes no assumptions about the structure of the flame and has proved successful in its application to turbulent non-premixed flames.
- There have been applications of PDF transport modelling to premixed flames in which convincing results have been obtained.
- The advantages of the approach lie in its potential for generality especially in cases where direct chemical effects may be important, but the computational cost is high and there are technical issues concerned with the modelling of mixing processes in the presence of the high scalar gradients typical of premixed flames.

Pope, S.B., PDF methods for turbulent reacting flows. Prog. Energy Combust. Sci. 11, 119– 192 (1985)

Pope, S.B., Cheng, W.K., The stochastic flamelet model of turbulent premixed combustion. Proc. Combust. Inst. 22, 781–815 (1989)

Jones, W.P., The joint scalar probability density function. In: Launder, B.E., Sandham, N.D. (Eds.) Closure Strategies for Turbulent and Transitional Flows, Cambridge University Press, Cambridge, UK (2002)

Lindstedt, R.P., Vaos, E.M., Transported PDF modelling of high-Reynolds number premixed turbulent flames. Combust. Flame 145, 495–511 (2006)

Other methods: Conditional Moment Closure (CMC)

- Another approach that has proved successful in non-premixed combustion is the Conditional Moment Closure (CMC) approach, in which the fluctuations of all variables about the conditional mean mixture fraction are assumed to be small.
- In principle the CMC approach could be extended to treat premixed flames, possibly by using the reaction progress variable as a conditioning variable. The use of a marker field variable has been suggested, but it is questionable whether this would bring any advantage over the existing G-equation approach.
- One promising avenue is the Conditional Source Term Estimation (CSTE) approach, which is closely related to CMC and which may provide a more realistic way to model chemical effects in premixed flames.

Bilger, R.W., Marker fields for turbulent premixed combustion. *Combust. Flame* 138, 188–194 (2004)

Grout, R.W., An age extended progress variable for conditioning reaction rates. *Phys. Fluids* 19, 105107 (2007)

Grout, R.W., Bushe W.K., Blair C., Predicting the ignition delay of turbulent methane jets using conditional source term estimation. *Combust. Theory Model.* 11, 1009–1028 (2007)