Turbulent Combustion: Modelling and Applications

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Structure of lectures

Day 1: The context
Introduction to combustion devices; gov. eqtns and the fundamental problem of turbulent combustion; classifications; “bird’s eye” view of modern turb. comb. research

Day 1-2: Revision of basics
Some fundamental aspects of turbulence and mixing; a revision of some laminar flame problems

Day 3: Modelling & applications
Models: infinitely fast chemistry (EBU, ED etc); “laminar chemistry”; non-premixed & premixed flames (flamelet, CMC, PDF); other models for premixed

Day 4: Modelling & applications
Diesel and natural gas engines; autoignition; gas turbine combustion; extinction; soot and NOx

**PLEASE INTERRUPT AND ASK QUESTIONS!**

Main education targets:
(i) To build physical intuition;
(ii) To develop skills in turb combustion modelling;
(iii) To be able to put your own research in context.
Bibliography

Books:
  *Introductory level; background; basics on the various models*
  *Advanced level; revision of major modern models & techniques*
  *Fundamental combustion, good introduction to turbulent combustion*
  *Flamelet model, turbulent premixed flame speed*

Progress in Energy and Combustion Science (journal):
  *Theory and connections between models*
  *Focus on premixed flame structure and models*
  *Focus on ignition (application to diesel and g.t. engines)*
  *Focus on thickened flame model, CFD approach, thermoacoustics*
  *Focus on sprays, models for range of combustion modes*
Day 1: Introduction and Statement of the Problem

Main applications: WHY do we bother?

Governing equations: WHAT is the problem?

Flame classification

Major issues in modern turbulent combustion research

International Workshops
Primary energy sources - worldwide

Source: IEA Statistics
Primary energy sources - worldwide

Around 90% comes from combustion (coal, oil, natural gas, biofuels)

Figure 4. Total primary energy supply by fuel

1971
- Oil 44%
- Nat. gas 16%
- Coal 26%
- Hydro 11%
- Nuclear 1%

2014
- Oil 31%
- Nat. gas 21%
- Coal 29%
- Hydro 10%
- Nuclear 5%
- Other 2%

5 523 Mtoe

13 700 Mtoe

* In this graph peat and oil shale are aggregated with coal.

Source: IEA Key World Energy Trends 2016
Fossil fuel’s use for electricity

Source: IEA Statistics
Coal’s contribution is reducing
Machines that use fuels

Coal and solid fuels

In-furnace view of flame
o(100MW)

Liquid (diesel, kerosene, SAF)

Spray autoignition; o(10-100kW)

Nat Gas, (H2, NH3)

Hopkinson Lab (1bar)
o(10kW)

Drax power station, UK
o(1GW), biomass

GE/Alstom GT26; o(300MW)

Aeroengine; o(1MW)
per combustor

Wartsila marine engine (~80MW)

o(0.1m)

o(10MW)

o(200MW) take-off
“With some 100,000 years of development, [combustion] might be expected to be a mature technology. In fact, it is the least developed technology of modern engineering systems. Engineering systems with mature technology have computer models that are routinely used in analysis and can be used in the optimization of the geometry and operating conditions of new designs. Thus the wings of new models of jet aircraft have subtle geometry contours that greatly increase their efficiency. The same can be said for the new generation of fans in turbo-fan engines. Computer modeling of combustors is still at a fledgling stage and is only used peripherally in the development of new combustors. **Combustor development is still largely by cut-and-try testing in experimental rigs and in prototype and in-service engines and power plants**”.

Combustion: an area where application is ahead of the scientific understanding

Many different phenomena (chemistry, heat transfer, fluid mechanics, multi-scale, surface reactions, pollutants, large range of chemical timescales etc)

Huge range of length scales (0.01m – 10m)
Huge range of residence times (ms to s)
Huge range of power (1kW to 100MW)

Some of this range is taken care of by the high pressure (more mass flow per unit time and area); but the remaining (many orders of magnitude) is achieved by the turbulence.

Fundamental effect of turbulence on reaction:
As Reynolds number increases, range of eddy length- and time-scale increases, hence more flame area, hence more reaction rate per unit volume.
Question: why does a spark ignition engine work at both 600 and 6000 rpm?

But:
If residence time too short, combustion not complete. Finite-rate kinetics!

Also:
Even if combustion OK, how about pollutants (CO, NOx, soot)? Finite-rate kinetics!
Legislation drives technological innovation; but theory lags behind.
Combustion in a low-carbon future?

Aviation: difficult to see medium- and long-range airplanes with electric motors (need high energy storage with high kJ/kg); current focus on H2 (short/medium range) & SAF (long-range).

Shipping: ~ similar to aviation; focus on NH3? CH2OH? H2? Biofuels?

Road transport (passenger cars): easier to fully electrify.

Road transport (heavy goods): some use of fuels (H2? Biofuels?) likely.

Electricity production: coal is on its way out; natural gas will increase.

CCS: pre- or post-combustion?

Accidents, explosions, nuclear safety, fire safety: combustion science necessary

Battery fires!

E-fuels & biofuels.

Studying combustion (kinetics, heat transfer, fluid mechanics, multi-scale phenomena, laser-based methods, CFD, etc) helps develop insights for many other sectors.
Future CO2 stabilisation scenarios
(“450”=450 ppm CO2)

Source: IEA statistics; TPES: Total Primary Energy Supply
Future of combustion?

Even when we replace fossil fuels with biomass-derived or e-fuels (renewable electricity to fuels), high-T oxidation processes will be relevant. We need to develop technologies that:

• Offer higher fuel economy (i.e. reduce CO₂ per unit of output)
• Reduce other pollutants (NOx, SOx, particulates)
• Facilitate carbon capture and storage (pre- and post-combustion)
• Offer fuel flexibility (low-LCV fuels, various NGs, various oils etc)
• Promote e-fuels (Hydrogen, ammonia, methanol, other HCs)
• Are safe (fires, explosions)

• Most of these applications have high Reynolds number

• Turbulent combustion remains important!

• We must engage more with the fuel producer.
Combustion is governed by a set of equations expressing the principles of conservation of overall mass, momentum and energy ("Fluid Mechanics" & "Heat transfer") and mass of individual species ("Mass transfer"), supplemented with a set of closures for heat and mass fluxes and for chemical source terms ("Chemical kinetics"). They are reproduced below (from Echekki & Mastorakos, 2011) for demonstration:

Mass
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \]

Momentum
\[ \frac{D\mathbf{u}}{Dt} = \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \sum_{k=1}^{N} Y_k f_k, \]

Species k
\[ \frac{DY_k}{Dt} = \rho \frac{\partial Y_k}{\partial t} + \rho \mathbf{u} \cdot \nabla Y_k = \nabla \cdot (\rho \mathbf{v}_k Y_k) + \omega_k, \]

Total internal energy
\[ \frac{De}{Dt} = \rho \frac{\partial e}{\partial t} + \rho \mathbf{u} \cdot \nabla e = -\nabla \cdot \mathbf{q} - p \nabla \cdot \mathbf{u} + \boldsymbol{\tau} : \nabla \mathbf{u} + \rho \sum_{k=1}^{N} Y_k f_k \cdot \mathbf{v}_k \]

Closures
\[ \boldsymbol{\tau} = \mu \left[ (\nabla \mathbf{u}) + (\nabla \mathbf{u})^T \right] + \left( \frac{2}{3} \mu - \kappa \right) (\nabla \cdot \mathbf{u}) \mathbf{I} \]
\[ X_k \mathbf{v}_k = -D_k^m \nabla X_k \]
\[ \mathbf{q} = -\lambda \nabla T + \rho \sum_{i=1}^{N} h_i Y_i \mathbf{v}_i + R_u \sum_{i=1}^{N} \sum_{j=1}^{N} \left( \frac{X_j D_{T,i}}{W_i D_{ij}} \right) (\mathbf{v}_i - \mathbf{v}_j) + \mathbf{q}_{\text{rad}} \]
Governing equations – the fundamental problem 2

For demonstration, assume 1-step chemical reaction (Sp1 + Sp2 = Sp3). The chemical source term $\omega$ is written as:

$$w_1 = -A\rho Y_1 Y_2 \exp \left( -\frac{T_{\text{act}}}{T} \right)$$

**Observation 1:** If $T_{\text{act}}$ high, the reaction rate increases very steeply with temperature. The steep dependence of the reaction rate on the temperature is one of the most important aspects of combustion!

**Observation 2:** Species 1 and 2 are coupled; consuming one means consuming the other. Chemistry develops connections between the source terms of the various species. Never forget this!
Governing equations – the fundamental problem 3

In turbulent flows, we need **averaging**. Consider time- or ensemble-averaging first (same comment applies to LES filtering)

\[ u_i = \bar{u}_i + u'_i \]

\[ Y = \bar{Y} + Y' \]

\[
\frac{\partial \bar{Y}}{\partial t} + \frac{\partial (\bar{u}_k \bar{Y})}{\partial x_k} = \frac{\partial}{\partial x_k} \left( D \frac{\partial \bar{Y}}{\partial x_k} \right) - \frac{\partial (u'_i Y')}{\partial x_i} + \frac{\bar{w}}{\rho} \]

(assume constant density for ease of presentation)

\[
\bar{w}_i Y' \quad \text{Turbulent flux of species due to velocity fluctuation in i-direction (needs modelling)}
\]

\[
\bar{w}_C = A \left( Y_A + Y'_A \right) \left( Y_B + Y'_B \right) \exp \left[ - \frac{T_{act}}{\bar{T} + T'} \right]
\]

\[
\bar{w}_C \neq A \bar{Y}_A \bar{Y}_B \exp \left( - \frac{T_{act}}{\bar{T}} \right)
\]

**Observation 3: Evaluating mean reaction rate at the mean Y and mean T is very wrong!**

In general, \( \bar{w}_\alpha \neq f(\bar{Y}_1, \bar{Y}_2, ..., \bar{Y}_N, \bar{T}) \)
The fundamental problem 4 – example of thin premixed flame in CFD

If $\delta_R \ll L$, and $\frac{1}{2}$ of cell is reactants, the $\frac{1}{2}$ of cell is products:

volume averaged $T$, $<T>$ = 1200K

(and volume averaged $Y_{\text{fuel}} = Y_{F,0}/2$)

If, say, $T_{\text{act}} = 20000$K (typical hydrocarbon fuel value), $\exp(-T_{\text{act}}/<T>) = 5.8\times10^{-8}$

But $<\exp(-T_{\text{act}}/T)> = \frac{\exp(-T_{\text{act}}/300) + \exp(-T_{\text{act}}/2100)}{2} = 7.3\times10^{-5}$

Three orders of magnitude error!

General observation 4: The average of a non-linear function IS NOT equal to the function evaluated at the average value of its arguments.

$<f(x)> \neq f(<x>)$ if $f(x)$ is nonlinear
The fundamental problem – conclusion

Therefore, in turbulent combustion CFD, we *never* evaluate the reaction rate at the values of species mass fractions and temperature we are solving for.

Unless we are doing DNS, we need a *MODEL* for the mean reaction rate!

In LES, the sub-grid fluctuations are smaller, but model is still needed.

If LES reaches DNS resolution (as in some recent lab-scale simulations), the absence of a sub-grid combustion model is not catastrophic. *But to generalise good agreement from DNS-like simulations of lab-scale flames to practical situations is wrong!*

The Arrhenius term is driving turbulent combustion research. We do not yet have a fully predictive theory.

Practical devices are virtually always turbulent – we *rely* on the turbulence to get high reaction rate per unit combustor volume.
Flame classification and range of quantities of interest

Lab-scale (~10kW), swirling n-heptane spray flame (Marchione et al., CNF 2009):

Blue or yellow; long or short; stable or unstable: depending on mass flow rate of air, fuel, spray pattern, swirl number, combustor diameter etc…

Large differences in behaviour!
Flame classification

Premixed flame, stabilised on round disk. Model for afterburner or natural-gas gt flame.

Series of swirling premixed flames arranged in a circle, mimicking annular combustor.

Heptane spray flame in swirling air. Streamline sketch typical of burners.

Source: Mastorakos’s own research
Example: phenomena present in gas turbine combustors

- Primary & secondary atomization, dispersion
- Heat loss, radiation
- Fuel
- Air
- Chemical mechanism, turbulence-chemistry interactions
- Flame location
- Aerodynamics
- NOx, CO, soot, Temperature profile, velocity, vorticity
- Thermo-acoustics (coupling with combustor acoustics)
- Heat transfer

RED: Usual targets
BLUE: Models
Designing a combustor: OK, not quite a Herculian task, but still…

Interesting mythological trivia:
Hercules finally killed Hydra by bringing along his young nephew to apply *fire* in every head he was chopping off so new ones would not pop-up...

PhD student or engine manufacturer designing a new combustor…

- Thermoacoustics
- Soot
- Blow-off
- NOx
- Ignition
- Heat transfer
- Flashback
Little by little combustion science helps

Q: Is this improvement solely due to more knowledge on soot, or also due to better understanding of flame stabilization and spray?
Flame classification – wide spectrum!

“Premixed”: fuel + air fully mixed before flame

“Non-premixed”: fuel and air arrive at flame from separate sides; little overlap

“Stratified”, “Partially-premixed”: a mix between the two; propagation across a range of equivalence ratio

Spray flames: elements of all three above

Flames in gas turbines: all types can be present at different places, conditions, designs

Flames in diesel engines: non-premixed (and autoignition); more premixing in recent Low-T Combustion concepts

Flames in spark-ignition engines: premixed or stratified (and spark ignition)

Pollutants: some pollutants created post-flame; hence concept of well-stirred or imperfectly-stirred reactors and plug-flow reactors useful

“How much chemistry do we need in a real combustor CFD?”
Flame classification – wide spectrum!

Mixture fraction $\xi$: to be discussed later
For now: equal to fuel distribution, if no combustion

- **“Fully Premixed”**
- **“Stratified flames”:**
  - Probably best understood by premixed flame concepts
  - Work picking-up everywhere
- **“Edge flames”:**
  - Probably best understood by non-premixed flame concepts
  - Some recent work with DNS & experiments
- **“Non-Premixed”** (no edge, no propagation)

Relevant to spray

Mixture fraction

Distance normal to propagation

$\xi_{\text{lean}}$, $\xi_{\text{st}}$, $\xi_{\text{rich}}$
Laminar vs. turbulent combustion

Laminar burning velocity is the outcome of reaction/diffusion balance. Fundamental property of a fuel/oxidiser mixture.
Heat release rate per m\(^2\): \(\rho Y_{fu} S_L(LHV)\).

Laminar vs. turbulent combustion

Turbulence wrinkles and stretches flame and therefore increases flame surface area, therefore quicker burning. “Turbulent flame speed” $S_T$ depends on $u'$ and $S_L$, mostly. But too much $u'$ can kill flame. Very intensive research at present.

Modern turbulent combustion research

Wide spectrum of people, approaches, backgrounds, focal points.

More powerful computers \(\Rightarrow\) LES in industry becomes common.

*No model is fully OK for all combustion phenomena!*

Close collaborations between experiment and modelling.

Key questions preoccupying turbulent combustion researcher and practitioner:

“How much chemistry do I need in a real combustor CFD?”

“Which canonical combustion problem best represents my turbulent flame?”

“What makes my research publishable in CNF these days?”
Trends in modern turbulent combustion research

International Workshops:
- **Turbulent Non-premixed Flames**
  - Used to be targeting finite-rate kinetics (local extinction) in non-prem; now more on stratified flames. Piloted or bluff-body stabilised with two streams of unequal f. Lots of attention to model validation
- **Turbulent Premixed Flames**
  - Focused scientific discussions; more on physics, less on model success.
- **Turbulent Combustion of Sprays**
  - Piloted jet flame (Sydney), spray in co-flow (Delft, Rouen), swirl spray flame (Cambridge)
  - Focus on model validation (including evaporation)
- **Sooting Flames**
  - Focus on laminar flames
  - Some turbulent target flames (DLR, Adelaide)

- Do we need one for NOx? For NH3? For H2?
- International Symposium, regional conferences: more on fundamentals
- AIAA, ASME, SAE: more on applications
- Finite-rate kinetics, pollutants, flame structure still important points of research

- **VERY IMPORTANT**: dialogue between modellers and experimentalists is needed!
Trends in modern turbulent combustion research

RANS/LES

Our best estimate of the truth!

Experiment

DNS

Low-order physical modelling

Useful codes and intuition for realistic devices

Not one-way information route; everybody learns from everybody in turbulent combustion
Trends in modern turbulent combustion research

Careful: “If you are holding a hammer, you think everything is a nail”…

OK, but not everything is turbulent:
True. We need to follow laminar flame and chemistry developments.

LES vs RANS:
Both are used in industry; LES in research. Industry catches up.
Accuracy vs. cost; how many LES can industry do for design?

Lots vs. little chemistry:
For flame position, perhaps simple chemistry is OK (except autoignition); for pollutants and extinction, chemistry of some complexity needed. Current experience: 50-100 species in chemical mechanism.
Solve chemistry on-line (e.g. CMC, PDF, LEM, TFM) or use pre-tabulation (e.g. flamelet)?

Comprehensive vs. approximations:
Do we need to include complex evaporation, radiation, high-Ma etc in ALL simulations?
Conclusions – Day 1 (Context)

Practical applications of combustion: high Re

High Re *instrumental* for enabling large range of power from combustion devices

Combustion will be with us for decades

No model works for everything

Validation focused on physical phenomenon still needed (e.g. for blow-off, ignition, pollution etc)

LES becomes standard

Collaborations needed

A researcher in turbulent combustion is *always* under attack – “*not enough chemistry*” for the chemist; “*not enough fluids*” for the fluid mechanician; “*not practical enough*” for the industrialist…But: somewhere within there you get a useful answer – if you understand the key limitations, trends and dependencies.
Turbulent Combustion: Modelling and Applications

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Day 2: Background on turbulent mixing and some laminar flame phenomena

Turbulence modelling

Mixing and scalar dissipation

Autoignition

Well-stirred reactor

Laminar premixed and non-premixed strained flames

Heat loss vs. chemistry
Statistical description

*Randomness*: we cannot say with certainty that an event will or will not occur. For example, that “$u(t)$ will be between 10 and 11 m/s”.

![Diagram of statistical description](image)

- **Possible timeseries of a turbulent signal (e.g. u, T)**
- **Probability density function**
- **Time average** (for stationary flow)
  \[
  \overline{u} = \lim_{T \to \infty} \frac{1}{T} \int_0^T u(t) \, dt
  \]
- **Ensemble average** (for non-stationary)
  \[
  \overline{u} = \frac{1}{N} \sum_{i=1}^{N} u_i
  \]
PDF

\[ P(r) : \text{probability that } r < u < r + dr \]

Properties: \( P(r) > 0 ; \int_a^b P(r)dr = 1 ; \)

\[ r \text{ takes values only in } [a,b] ; [a,b] \text{ is called the sample space} \]

Probability that \( v_1 < u < v_2 = \int_{v_1}^{v_2} P(r)dr \)

In turbulence, \( P(u) \) nearly Gaussian.

For velocity, \([a,b]=[-\infty,\infty] \)

For scalar, \([a,b] \) bounded; \( P(\text{Temperature}) \) could have funny shapes...
Multivariate PDF:

Gives us the statistics of two quantities (for example: the velocities in two directions), and their relationship (in a statistical sense).

\[ P(u,v) = \text{probability that } u_1 < u < u_2 \text{ AND } v_1 < v < v_2 \]

Properties: \( P(u,v) > 0 \); \( \int_{a_1}^{b_1} \int_{a_2}^{b_2} P(u,v) du \ dv = 1 \)
Averaging with the PDF:

Mean of $u$ and of a function $f(u)$ and the variance $\sigma^2$ are given by:

$$\bar{u} = \int uP(u)du$$

$$\bar{f(u)} = \int f(u)P(u)du$$

$$\sigma^2 = \int (u - \bar{u})^2 P(u)du$$

$$= \bar{u^2} - 2\bar{u} \bar{u} + \bar{u}^2$$

$$= \bar{u^2} - \bar{u}^2$$

In turbulence parlance, the variance is the average of the squared *fluctuations*.
Typical iso-probability contours:

Correlation coefficient:

\[
\rho_{uv} = \frac{u'v'}{\sigma_u \sigma_v}
\]
Energy cascade & eddy scales

A. Turbulence has a large range of eddy sizes.
B. Large ones “break-up” to smaller ones due to instability.

A + B = “energy cascade”

Kinetic energy flows from large eddies to small ones, eventually the process stops due to viscosity.
Energy cascade & eddy scales

(Note: these images are not truly consistent, they are not from the same experiment, they are used for illustrating the concept.)
Velocity, length, and timescales: large-eddy scales

Turbulent kinetic energy $k$: $k = \frac{1}{2} (u'_i u'_i) = \frac{1}{2} (u'_1 u'_1 + u'_2 u'_2 + u'_3 u'_3)$

Typical or “characteristic” turbulent velocity fluctuation $u$: $k = \frac{3}{2} u^2$

$L_{\text{turb}}$: size of large eddies = o(width of flow)

$T_{\text{turb}} = L_{\text{turb}} / u$: eddy turnover time

eddy lifetime

integral timescale
**Vortex stretching:**

The fundamental mechanism by which eddies break apart, vorticity gets concentrated in patches, turbulence is 3D, small-scales become isotropic etc

Conservation of angular momentum in inviscid, incompressible fluid:

\[
\omega_2 > \omega_1 \\
\omega_3 > \omega_2
\]

Vortex-induced flow causes further stretching

“Spaghetti”
What is an “eddy”? 

Vorticity is concentrated in tubes or sheets; with quiet fluid around them. “3-D Spaghetti” model.

High scalar & kinetic energy dissipation regions highly localised.
Turbulence modelling

Governing equations for mean U or scalar have higher-order correlations.

Turbulent scalar fluxes and Reynolds stresses need closure. Usual closure: gradient hypothesis

Important concept: energy cascade and kinetic energy dissipation

\[
\begin{align*}
\overline{u'_i u'_j} &= -\nu_{turb} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij} \\
\overline{u'_j \phi'} &= -D_{turb} \frac{\partial \overline{\phi}}{\partial x_j}
\end{align*}
\]

\[
\eta_K = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4}
\]

\[
\tau_K = \left( \frac{\nu}{\varepsilon} \right)^{1/2}
\]

\[
v_K = \left( \nu \varepsilon \right)^{1/4}
\]

Kolmogorov scales

\[
\begin{align*}
\eta_K &= L_{turb} R_e^{-3/4} \\
\tau_K &= T_{turb} R_e^{-1/2} \\
v_K &= u R_e^{-1/4}
\end{align*}
\]

Dissipation \approx \frac{u^2}{(eddy \ lifetime = L_{turb}/u)}
Turbulence modelling

$k$-$\varepsilon$ turbulence model: the workhorse in industry, initial condition for LES etc.

Do not alter “constants”; if it does not work, use another model (Reynolds stress, LES etc)

\[
\begin{align*}
\frac{\partial k}{\partial t} + \bar{u}_i \frac{\partial k}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \nu_t \frac{\partial k}{\sigma_k \partial x_i} \right) + P_k - \varepsilon \\
\frac{\partial \varepsilon}{\partial t} + \bar{u}_i \frac{\partial \varepsilon}{\partial x_i} &= \frac{\partial}{\partial x_i} \left( \nu_t \frac{\partial \varepsilon}{\sigma_\varepsilon \partial x_i} \right) + c_{\varepsilon 1} \frac{\varepsilon}{k} P_k - c_{\varepsilon 2} \frac{\varepsilon^2}{k} \\
\nu_t &= C'_\mu \frac{k^2}{\varepsilon} \\
P_k &= \frac{1}{2} \nu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)^2 \\
C'_\mu &= 0.09, \ c_{\varepsilon 1} = 1.44, \ c_{\varepsilon 2} = 1.92, \ \sigma_k = 1.0, \ \sigma_\varepsilon = 1.3
\end{align*}
\]
Turbulent mixing – molecular chaos / random walk

Continuum (Eulerian) vs. “particle” (Lagrangian) approach: Do \( k \) jumps per unit time, each a distance \( \Delta x \), in random direction; probability that particle will be in position \( m \) is:

\[
P(m, K) = \frac{1}{\sqrt{2\pi} \sqrt{K}} \exp \left( -\frac{m^2}{2K} \right)
\]

This is the solution to the 1-D diffusion equation with diffusivity \( D=(k\Delta x)\Delta x/2 \); \( k\Delta x \) can be understood as a characteristic velocity.

Basic idea behind Brownian motion, random walks, PDF method etc.
Turbulent mixing – large scale dispersion


In 1-D for simplicity:

\[ X(t) = \int_0^t V(t') dt' \]

\[ \frac{dX^2(t)}{dt} = 2V^2 \int_0^t R_L(\tau) d\tau \]

\[ R_L(\tau) = \frac{V(t)V(t+\tau)}{V^2} \]

\[ T_L = \int_0^\infty R_L(\tau) d\tau \]
Turbulent mixing – large scale dispersion

Short times: \( \overline{X^2(t)} = \overline{V^2} t^2 \)  
So, for \( \overline{X^2(t)} = 2D_{turb} t \)  
\( D_{turb} = \frac{1}{2} \overline{V^2} t \)

Long times: \( \overline{X^2(t)} = 2\overline{V^2} T_L t \)  
So, for \( \overline{X^2(t)} = 2D_{turb} t \)  
\( D_{turb} = u^2 T_L \)

Turbulence has “memory”. It is not like white noise.

Distinction between short-time and long-time mixing needed often in turbulent combustion:

(i) growing flame kernel experiences only a range of eddies;
(ii) growth of V-flame brush;
(iii) attachment points vs. far-field regions;
(iv) attention to fuel inlets needed.
Turbulent mixing – scalar dissipation

\[
\begin{align*}
\frac{\partial (\bar{\rho} \bar{\xi})}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_k \bar{\xi})}{\partial x_k} &= \frac{\partial }{\partial x_k} \left( \bar{\rho} D \frac{\partial \bar{\xi}}{\partial x_k} \right) - \frac{\partial (\bar{\rho} \bar{u}_k' \bar{\xi}''')}{\partial x_k} \\
\frac{\partial (\bar{\rho} g^2)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_i g^2)}{\partial x_i} &= \frac{\partial }{\partial x_i} \left( \bar{\rho} D g \frac{\partial g}{\partial x_i} \right) + 2\bar{\rho} D_{turb} \left( \frac{\partial \bar{\xi}}{\partial x_i} \right)^2 - C_d \bar{\rho} \bar{\varepsilon} g^2 \\
\end{align*}
\]

Above equations are for mean and variance of a passive scalar (i.e. no source term). Expressed in density-weighted averages.

Gradient approximation has been used: not good in general for complex flows, hence the motivation for LES.

Scalar dissipation: very important quantity in turbulent combustion. Appears in premixed & non-premixed models.

Usual model:
scalar dissipation = (energy to be dissipated)/(eddy timescale)
"Energy cascade" idea for the scalar.
Turbulent mixing – scalar dissipation

Small-scale intermittency of velocity field leads to filament-like structure of scalar dissipation field. Smallest scale is the Bachelor scale:

\[ \lambda_B = \eta_K \text{Sc}^{-1/2} \]
Turbulent mixing – scalar dissipation

Conditional scalar dissipation appears often in models (will be discussed later)
Turbulent mixing – probability density function of scalars

Instantaneous

Mean

Scalar PDF is bounded [0,1]
Turbulent mixing – probability density function of scalars
Inertial range

Question: Can I have some universal theory for the energy distribution across eddy size?

Answer: Kolmogorov said “yes”, under certain conditions.

Assumptions: (i) dissipation independent of scale (again); (ii) viscosity is important only at small scales (again). Hence: \( E(\kappa) = f(\kappa, \varepsilon) \).

Units: \( \kappa: \text{m}^{-1} ; E: \text{m}^3\text{s}^{-2} ; \varepsilon: \text{m}^2\text{s}^{-3} \). 3 quantities, 2 units, therefore:

\[
E(\kappa) = C\kappa^{-5/3}\varepsilon^{2/3}
\]

Very strong experiment evidence for the “\(-5/3\) law” for all flows. One of the “footprints” of a turbulent signal.
Energy spectra

It is always a good idea (DNS, LES, experiment) to check your spectra. A -5/3 region should be evident if Re is high enough.
Resolution

Well-resolved DNS of premixed flames in Intense shear

$\delta_{th}/\Delta x \sim 40$ (many points across flame)

$\eta_k/\Delta x \sim 2$ (finer than Kolmogorov)

Dissipation spectrum

Kolla et al, CST 2016
Taylor hypothesis

If mean flow mainly in one direction, and $\sqrt{k} (= u) \ll \bar{u}$, then:

$$\frac{\partial}{\partial t} \approx \bar{u}_1 \frac{\partial}{\partial x}$$

Hence, a one-point temporal record is equivalent to a two-point measurement, and hence we can measure ("estimate", rather) dissipation:

$$\varepsilon = \frac{15 \nu}{\bar{u}_1^2} \left( \frac{\partial \bar{u}_1'}{\partial t} \right)^2$$

Also, integral timescale is $T'_{turb} = L_{turb} / \bar{u}$

And eddy turnover time is $T_{turb} = L_{turb} / u$
Instrument response

How to estimate the fastest motion we may expect in an Eulerian measurement:

Hence, fastest frequency is $U/\eta_K$, *NOT* $1/T_{turb}$, $1/T_{turb}$, or $1/\tau_K$. 
**Convergence of averages**

Question: if I want to estimate the mean to a given accuracy, for how long should I be measuring?

$U_T$: true mean; $U_{est}$: estimated mean after $N$ statistically-independent samples; $\sigma^2$: true variance. Then:

$$\frac{|U_{est} - U_T|}{U_T} = \frac{\sigma}{U_T} \frac{1}{N^{1/2}} = \frac{\sigma}{U_T} \left(\frac{T'_{turb}}{T}\right)^{1/2}$$

$T/T'_{turb}$: estimate of the number of statistically independent measurements over time period $T$ in the turbulent signal with integral timescale $T'_{turb}$. Error $\to 0$ as $N \to$ infinity. Error depends on $\sigma$.

Millions of data points mean little, if not statistically independent.

“Flow-through times” – please avoid; it means almost nothing. Each point in your flow will converge differently.
Next few slides: some laminar flame concepts

- Autoignition with and without heat losses
- Well-stirred reactor
- Laminar strained diffusion flame
- Laminar strained premixed flame

- Conclusions we will draw:
  - Introduce some concepts and quantities needed later
  - balance of diffusion/convection and chemistry governs behaviour – how you capture this phenomenon distinguishes turbulent combustion modelling approaches.
Simple chemical model

1-step chemistry: \( F + n \, O \rightarrow (1+s) \, P \)

\[ 1 \text{kg} \, F + S(=n \, M_O/M_F) \text{kg} \, O \rightarrow (1+S) \text{kg} \, P \]

Assume constant \( c_p, \, \text{Le}=1, \, D=\text{constant}, \, \text{adiabatic}. \) Then:

\[
\dot{w}_{fu} = -A \frac{MW_{fu}}{MW_{fu} \, MW_{ox}} \rho^2 \, Y_{fu} \, Y_{ox} \, \exp\left(-\frac{E}{RT}\right)
\]

\[
\rho \frac{\partial Y_{fu}}{\partial t} + \rho U_i \frac{\partial Y_{fu}}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial Y_{fu}}{\partial x_i} \right) + \dot{w}_{fu}
\]

\[
\rho \frac{\partial T}{\partial t} + \rho c_p U_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} \right) - Q \dot{w}_{fu}
\]

\[
\Rightarrow Z = Q Y_{fu} + c_p T = \text{conserved scalar}
\]

\[
= Q Y_{fu,0} + c_p T_0 \iff Y_{fu} = Y_{fu,0} - c_p (T - T_0) / Q
\]
Key conclusion: reaction rate very non-linear with $T$; has a maximum due to coupling between $T$ reached & conversion of reactants.
Autoignition without heat losses

Assume constant $P$, $c_p$, Le=1, adiabatic, homogeneous. Assume small reactants consumption until autoignition. Linearize reaction rate.

\[
\frac{\partial T}{\partial t} = \left[ \frac{Q}{c_p \text{MW}_{fu} \text{MW}_{ox}} \rho_0 A Y_{fu,0} Y_{ox,0} \right] \exp\left(-\frac{E}{R^0 T}\right)
\]

\[
\exp\left(-\frac{E}{R^0 T}\right) = \exp\left[-\frac{E}{R^0 T_0 (1 + \Delta T / T_0)}\right] = \exp\left[-\frac{E}{R^0 T_0 (1 - \Delta T / T_0 + \ldots)}\right] \Leftrightarrow \exp\left(-\frac{E}{R^0 T}\right) \approx \exp\left(-\frac{E}{R^0 T_0}\right) \exp\left[\frac{E(T - T_0)}{R^0 T_0^2}\right]
\]

\[
\frac{\partial T}{\partial t} = B \exp\left(-\frac{E}{R^0 T_0}\right) \exp\left[\frac{E(T - T_0)}{R^0 T_0^2}\right] \Leftrightarrow t = \frac{1}{B} \frac{R^0 T_0^2}{E} \exp\left[\frac{E}{R^0 T_0}\right] \left(1 - \exp\left[-\frac{E(T - T_0)}{R^0 T_0^2}\right]\right)
\]

\[
t(T \rightarrow \infty) = "\text{ignition delay time}" \quad \tau_{ign} = \left( \frac{Q}{c_p \text{MW}_{fu} \text{MW}_{ox}} \rho_0 A Y_{fu,0} Y_{ox,0} \right)^{-1} \frac{R^0 T_0^2}{E} \exp\left(\frac{E}{R^0 T_0}\right)
\]
Autoignition without heat losses

Trends:
- As temperature increases, the ignition time decreases very fast.
- As $P$ increases, $t_{\text{ign}}$ decreases.

Realistic chemistry:
- Arrhenious behaviour often; complexities arise for heavy HCs
Autoignition with heat losses

During induction time, heat losses to walls. Ignition time longer than without heat losses

\[
\frac{\partial T}{\partial t} = \frac{1}{\rho c_v} Q \dot{w}_{fu} - \frac{A_V}{V \rho c_v} h(T - T_0) = G - L
\]
Autoignition with heat losses

Graphical solution:

Excessive heat losses ➔ no ignition.

Defines “Autoignition Temperature”. It is NOT a fundamental property.
"Longwell Bomb"

All quantities uniform inside, steady, constant $P$, adiabatic
Residence time $= \frac{\text{volume}}{\text{flow rate}}$
“out” = “inside”; different from “in”
The Well-Stirred Reactor

Species: \[ \dot{m} \left( Y_{i,\text{out}} - Y_{i,\text{in}} \right) = \dot{w}_i V \]

Energy: \[ \dot{m} c_p \left( T_{\text{out}} - T_{\text{in}} \right) = -\dot{w}_{fu} V Q \]

\[ \dot{w}_{fu} = -A \frac{MW_{fu}}{MW_{fu} MW_{ox}} \rho^2 Y_{fu} Y_{ox} \exp \left( -\frac{E}{R^0 T} \right) \]

\[ Y_{fu} = Y_{fu,\text{in}} - c_p (T - T_{\text{in}}) / Q \]

\[ Y_{ox} = Y_{ox,\text{in}} - S c_p (T - T_{\text{in}}) / Q \]

Heat Loss: \[ \frac{\dot{m}}{V \rho} (T - T_{\text{in}}) = C f(T) \]

Heat Generation: \[ t_{res} \equiv \frac{V \rho}{\dot{m}} \]
The Well-Stirred Reactor: extinction

\[ \frac{\dot{m}}{V\rho} (T - T_{in}) = C f(T) \]

Term in energy eq.

frozen (extinguished)

burning

stable

unstable

realizable conditions

\[ HT_1 \]

\[ HT_2 \]

\[ HT_{cr} \]

\[ HT_3 \]

\[ S_1 \]

\[ S_2 \]

\[ S_3 \]

\[ S_4 \]
Extinction

Trends:
- Extinction due to a balance between residence time & kinetics.
- As $T_{in}$ increases, stability improves.
- As $t_{res}$ decreases, T decreases and then suddenly extinction occurs
- Basic physics behind “S-shaped curve” of laminar flames
- Applications: WSR models used in GT modelling; flame blow-off
Laminar non-premixed (or diffusion) flames

- Laminar non-premixed flame structure not necessarily preserved in turbulent flames
- Key issues: location, extinction, radiation, CO, NO, soot

Fig. 4.2 Schematic of a laminar non-premixed flame of fuel issuing from a jet in air. Distributions of fuel, oxygen and products across the flame. The temperature follows the distribution of products.

T, Y in mixture fraction space (will be discussed in next slide)
Mixture fraction: key concept to understand non-premixed flames

- Conserved scalars (in 2-D for simplicity):

\[
\rho U \frac{\partial Y_{fu}}{\partial x} + \rho V \frac{\partial Y_{fu}}{\partial y} = \frac{\partial}{\partial x} \left( \rho D \frac{\partial Y_{fu}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho D \frac{\partial Y_{fu}}{\partial y} \right) - \dot{w}_{fu}
\]

\[
\rho U \frac{\partial Y_{ox}}{\partial x} + \rho V \frac{\partial Y_{ox}}{\partial y} = \frac{\partial}{\partial x} \left( \rho D \frac{\partial Y_{ox}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho D \frac{\partial Y_{ox}}{\partial y} \right) - S \dot{w}_{fu}
\]

\[
\rho c_p U \frac{\partial T}{\partial x} + \rho c_p V \frac{\partial T}{\partial y} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + Q \dot{w}_{fu}
\]

\[
\rho U \frac{\partial (Y_{fu} Q + c_p T)}{\partial x} + \rho V \frac{\partial (Y_{fu} Q + c_p T)}{\partial y} = \frac{\partial}{\partial x} \left[ \rho D \frac{\partial (Y_{fu} Q + c_p T)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \rho D \frac{\partial (Y_{fu} Q + c_p T)}{\partial y} \right]
\]

\[
\rho U \frac{\partial (Y_{ox} Q + Sc_p T)}{\partial x} + \rho V \frac{\partial (Y_{ox} Q + Sc_p T)}{\partial y} = \frac{\partial}{\partial x} \left[ \rho D \frac{\partial (Y_{ox} Q + Sc_p T)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \rho D \frac{\partial (Y_{ox} Q + Sc_p T)}{\partial y} \right]
\]

\[
\rho U \frac{\partial (Y_{fu} - Y_{ox} / S)}{\partial x} + \rho V \frac{\partial (Y_{fu} - Y_{ox} / S)}{\partial y} = \frac{\partial}{\partial x} \left[ \rho D \frac{\partial (Y_{fu} - Y_{ox} / S)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \rho D \frac{\partial (Y_{fu} - Y_{ox} / S)}{\partial y} \right]
\]
Mixture fraction

- The mixture fraction:

\[
\xi = \frac{\left( Y_{fu} - Y_{ox} / S \right) - \left( Y_{fu} - Y_{ox} / S \right)_2}{\left( Y_{fu} - Y_{ox} / S \right)_1 - \left( Y_{fu} - Y_{ox} / S \right)_2}
\]

\[
\xi = \frac{Y_{fu} - Y_{ox} / S + Y_{ox,0} / S}{Y_{fu,0} + Y_{ox,0} / S}
\]

- Stoichiometric mixture fraction: when \( Y_{fu} = Y_{ox} / S \).

- Knowledge of \( \xi \) gives everything:

\[
\bar{Y}_\alpha = \int_0^1 Y_{\alpha}(\xi) P(\xi) d\xi
\]

Stream 1: “fuel”

Stream 2: “air”

No fuel in air, no air in fuel

No source term!
Mixture fraction

• Mixture fraction is an extremely important concept in non-premixed & spray reacting flows:
  • Gives mass fraction of fluid originated from fuel stream
  • Covers the vast majority of practical problems (one-fuel combustion)
  • Determination of mixing de-coupled from reaction (mixture fraction mixes in flow like any passive scalar)
  • For systems with more than one fuel or air stream, one can use “multiple mixture fractions” (Fox’s book, 2003)
  • Note: when differential diffusion effects are considered, different ways to define mixture fraction become possible
Laminar diffusion flames: flame sheet model

- Flame pegged on stoichiometric iso-surface; reactants come to flame from either side; do not penetrate; \( w=0 \) everywhere except at flame sheet.

\[ T_f = Y_{fu,0} \xi_{st} \left( \frac{Q}{cp} - (T_{ox,0} - T_{fu,0}) \right) + T_{ox,0} \]
Laminar diffusion flames: finite rate chemistry

- Counterflow flame: a canonical problem highlighting the balance between fluid mechanics (mixing, strain, scalar dissipation) and chemistry. Mixing controlled by strain rate $A$ (equivalent to scalar dissipation $N = D [\frac{\partial \xi}{\partial x}]^2$).

\[
\xi = \frac{1}{2} [1 + erf(\eta)]
\]
\[
\eta = \frac{x}{\sqrt{2D/A}}
\]
\[
2N = \frac{A}{\pi}
\]

Max $N$ across layer; denote by $N_0$

Model for scalar dissipation in flamelet and CMC turbulent combustion methods
Laminar diffusion flames: finite rate chemistry

- Solve (i) either laminar diffusion flame in physical space and store results; or (ii) solve directly in mixture fraction space
- Steady, transient
- Chemistry to any complexity can be used
- See Peters (2000)
- Structure of equations (const. $c_p$):

\[
\rho \frac{\partial T}{\partial t} = \rho N(\xi) \frac{\partial^2 T}{\partial \xi^2} + w_T(Y_1, Y_2, ..., Y_N, T)
\]

\[
\rho \frac{\partial Y_\alpha}{\partial t} = \frac{\rho N(\xi)}{L e_\alpha} \frac{\partial^2 Y_\alpha}{\partial \xi^2} + w_\alpha(Y_1, Y_2, ..., Y_N, T)
\]

Flamelet equations
• Finite rate implies: (i) overlap between fuel and air; lower T; curved corners. (ii) possibility of extinction; (iii) needed for pollutants.
• Effects more pronounced as strain rate (or scalar dissipation) increases.

Borghesi, PhD, Univ. of Cambridge; using reduced CH4 mechanism from Massias et al, CTM, 1999
As scalar dissipation increases, flame burns OK, but at reduced T and slightly reduced radical levels.
• As scalar dissipation increases, some pollutants may change.
• Extinction scalar dissipation: denotes fastest possible mixing rate that the flame can survive. Up to this point, flame burns, but at reduced T. After a critical scalar dissipation, no combustion possible.

GRI3, skeletal (Smooke), modified 1-step (Q=f(φ))

GRI 2.11 & reduced

~400K
Further demonstration of Damköhler number effect

- Simple isothermal problem, reaction-diffusion balance. See overlap of reactants as Da decreases.

\[
\frac{\partial \phi_1}{\partial t} = \frac{\partial^2 \phi_1}{\partial \eta^2} - Da \phi_1 \phi_2 \\
\frac{\partial \phi_2}{\partial t} = \frac{\partial^2 \phi_2}{\partial \eta^2} - Da \phi_1 \phi_2 \\
\phi_1 (\eta = 0) = 0 \\
\phi_1 (\eta = 1) = 1 \\
\phi_2 (\eta = 0) = 1 \\
\phi_2 (\eta = 1) = 0
\]
Laminar counterflow premixed flame

- Solve with laminar flame code; then store results for use in turbulent flame model
  - Some models only use $S_L$
  - Other use species mass fractions vs. progress variable $c$
  - Other use $w_k(c)$

Freely propagating flame

Strained flame (“back to back”)
Flame stretch

Flame area increases due to stretch. Stretch due to aerodynamic strain and curvature. Local consumption depends additionally on Lewis number.

\[ S = \frac{1}{A} \frac{dA}{dt} \]

\[ \frac{1}{A} \frac{dA}{dt} = a_T + 2u_d h_m \]

Fig. 5.6 Local effects of strain and curvature on the flame: (left) positive straining; (centre) negative straining; (right) curvature and propagation.

From Cant & Mastorakos (2007)
Turbulent flame speed

Turbulent flame: more area than in laminar flames.

Damköhler hypothesis:
(nearly 60 years ago)

\[ \frac{\rho_u S_i^o A_T}{\rho_u S_i A} = \frac{A_T}{A} = 1 + \frac{u'}{s_L} \]

for large turbulence level (small scale turbulence) diffusivity ratio plays a role:

\[ \frac{S_T}{S_i^o} \approx \left( \frac{u'\Delta}{s_L^o \delta} \right)^{1/2} \]

\( S_T \) is a challenging quantity to predict – recent advances

From Swaminathan (Lecture notes) & Cant & Mastorakos (2007)
Turbulent flame speed

Turbulent flame: more area than laminar. Estimating area leads to $S_T$ model

\[
\frac{S_T}{S_L} = 1 + f\left(\frac{L_{turb}}{\delta}\right) \left(\frac{u' \delta}{S_L}\right)^n
\]

“Bending effect”

Turbulent premixed flame diagram

From Cant & Mastorakos (2007)
How does laminar flame respond to strain rate fluctuations?

Table 1: Cases investigated. The configuration is indicated by P for ‘premixed’ and NP for ‘non-premixed’.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Pressure (bar)</th>
<th>$T_u$ (K)</th>
<th>Configuration</th>
<th>$N_{0,ext}$ $(s^{-1})$</th>
<th>$K_{ext}$ $(s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>1</td>
<td>403</td>
<td>P, NP</td>
<td>1830 (P), 249 (NP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>571</td>
<td>P, NP</td>
<td>9674 (P), 945 (NP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>617</td>
<td>NP</td>
<td>1345</td>
<td></td>
</tr>
<tr>
<td>$n$-C$<em>{12}$H$</em>{26}$</td>
<td>1</td>
<td>403</td>
<td>P</td>
<td>474</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>489</td>
<td>NP</td>
<td>525</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>571</td>
<td>P, NP</td>
<td>3031 (P), 2028 (NP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>617</td>
<td>NP</td>
<td>3353</td>
<td></td>
</tr>
</tbody>
</table>
How does laminar flames respond to local extinction?

Figure 1: Extinction transient for CH$_4$ flames at $p=1$ bar.

Paxton, Giusti, Egolfopoulos, Mastorakos, CNF 2019
How does laminar premixed flame respond to strain rate fluctuations and local extinction?

Paxton, Giusti, Egolfopoulos, Mastorakos, CNF 2019

As OH decreases, nothing left to consume CH2O, so CH2O accumulates. Theoretical validation of the conjecture of Kariuki et al. (PROCI 35) with CH2O-PLIF in turbulent premixed flame.
Heat loss (conv / diff) vs. Heat generation

In both autoignition and WSR, the balance between heat loss (by convection or diffusion) and heat generation (by chemical reaction) determines the nature of the solution.

In laminar non-premixed flames, reaction will cease if the strain rate $A$ is too high. Reaction rate can increase as $A$ increases, but $T$ decreases, and eventually extinction occurs.

Laminar flame simulations and experiments provide information on (i) chemical kinetics; (ii) flame structure.

Both needed in turbulent non-premixed flame models, if these are targeting finite-rate kinetic effects. If the turbulent flame simulation only targets flame length, perhaps infinitely-fast chemistry is OK.

Similarly for premixed flames: in some turbulent flame models, we need only $S_L$. In others we need $w(c)$, and we can choose from freely propagating flame, strained single («burnt to unburnt»), or strained double («unburnt to unburnt») counterflow flame.
Please do not use the phrase “turbulence – chemistry interactions” in vain…

For some, this term means only the large-scale flapping of a reaction zone that remains unchanged from the laminar structure.

For some, this term means only the small-scale fluctuations of the mixing rate (e.g. Kolmogorov-scale phenomena, strain fluctuations, dissipation rate fluctuations etc).

For some, this term means the statistics of the mixture generated before the flame.

My advice:

Specify which effect of turbulence you are talking about.

Think hard who your audience is – and what they are thinking and what their prejudices are.

Better to discuss these “interactions” through an equation.

Distinguish between large-scale vs. small-scale, average vs. instantaneous.
Conclusions – Day 2

Basic turbulence ideas needed in turbulent combustion:
- Reynolds decomposition
- Diffusivity, range of scales, dissipation

Basic laminar combustion concepts needed for turbulent flames:
- Balance of heat loss vs. heat generation
- Structure of non-premixed flame
- Structure of premixed flame

Some turbulent combustion models do not take local stretch effects into account; these approaches may fail for finite-rate kinetic effects, local extinction, re-ignition, soot and other quantities.