Lecture 7:

Ch. 8: Pollution from Combustion

&

Turbulent Combustion – A Brief Introduction (non-examinable)

Pollutants from Combustion - Objectives

- technological and social problem of air pollution
- the nature of pollutants emitted from combustion sources
- some features of the chemistry of pollutant generation
- typical techniques used to reduce pollution.

Tech. & Social issues

$$\text{(pollutant emission)} = \text{(population)} \times \text{(economic activity per person)} \times \text{(pollutant per unit economic activity)}$$

Why do we care?

There are various reasons why we must fight air pollution. We could categorize these reasons as:

- economic, e.g. destruction of property by a particular chemical;
- aesthetic, e.g. destruction of monuments from acid rain and the unsightly haze in the atmosphere;
- related to sustainability: carbon dioxide contributes to the greenhouse effect and acid rain destroys forests; and
- related to health: some pollutants cause serious harm, either immediately upon exposure or long-term, and even death.

Smog: smoke and fog

a cocktail of chemicals

Sources – Regulated pollutants

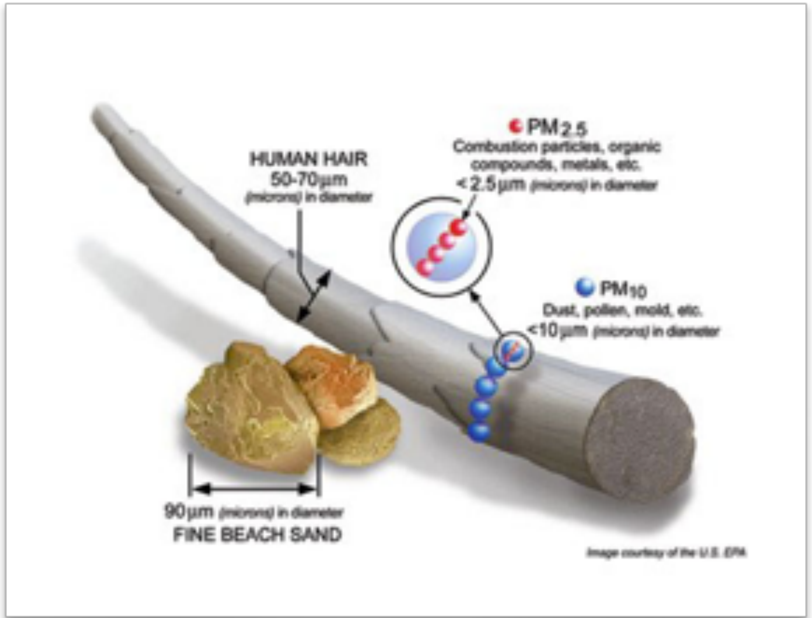
UNIVERSITY OF CAMBRIDGE

Source category	CO	SOx	NOx	PM10	VOC
Transportation	43.49	0.99	7.26	1.51	5.08
Electricity generation	4.67	16.55	10.59	1.10	0.67
Industrial processes	4.69	3.16	0.60	1.84	7.86
Solid waste disposal	3.06	0.02	0.10	0.26	0.69
Miscellaneous	7.18	0.01	0.21	0.73	2.59
Total	62.09	20.73	18.76	5.44	16.89

(million tons per year)

CO_2, UHC,
Heavy metals & Dioxins

Mainly from open & uncontrolled fires



Pollutants depends on the fuel used

Fuel switching (coal to CH_4) – obvious way to reduce, but may lead to emission of other pollutants

Effects and Solutions

CO_2 : effects: Green house gas – global warming,
mitigation routes: efficiency improvement or C-free sources/fuels

CO : effects: extremely dangerous, can cause death, due to flame quenching, too short residence time
routes: lean burn (excess air), fine droplets, avoid misfire in SI engines catalytic oxidation (catalytic convertor used in cars)

SOx: effects: S in fuel (coal, diesel), cause acid rain – environmental issues respiratory problems, can cause death (London Smog, 1952/Dec., 4000 deaths)
routes: mostly scrubbing with limestone
($CaCO_3 + SO_2 + 0.5\ O_2 \rightarrow CaSO_4 + CO_2$)
scrubbers' cost can be a large % of power station
not a problem for modern diesel vehicles – diesel is mostly S free!!

Effects and Solutions

NOx :

<u>effects</u>: (NO + NO2), NO + 0.5O2 -> NO2

Photo-chemical smog

Acid rain – nitric acid, NO + 2 O2 -> NO2 + O3

O3 – respiratory problems, impaired vision

At high altitude, NO + O3 + sun light -> NO2 + O2 – Ozone hole

three types: Fuel NO - fuel bound N2

Prompt NO - due to chemical reaction between N2 and CH

Thermal NO – dominant source in combustion

$$N2 + O \longrightarrow NO + N$$

$$N + O2 \longrightarrow NO + O$$

$$O2 \rightleftharpoons 2O$$

(See Q3 in the example sheet)

NO↑ resid. time & T↑

<u>routes</u>:

Lean burn,

RQL combustion

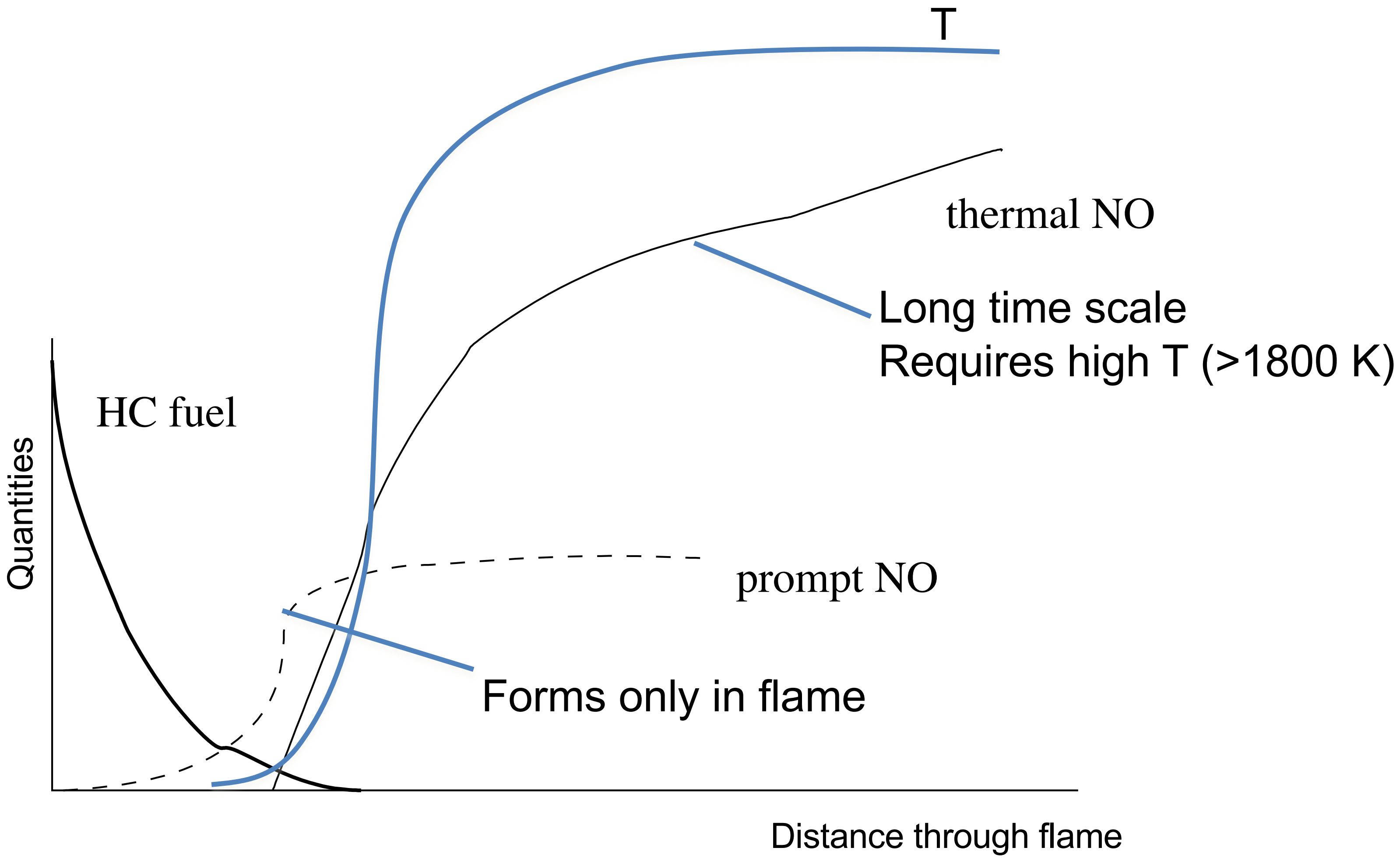
EGR

Oxy-fuel combustion

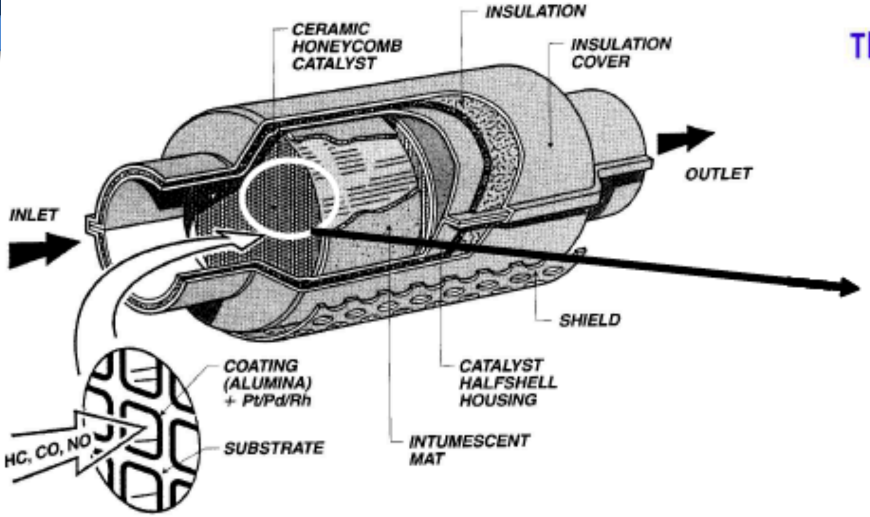
NOx reburn

Catalytic reduction

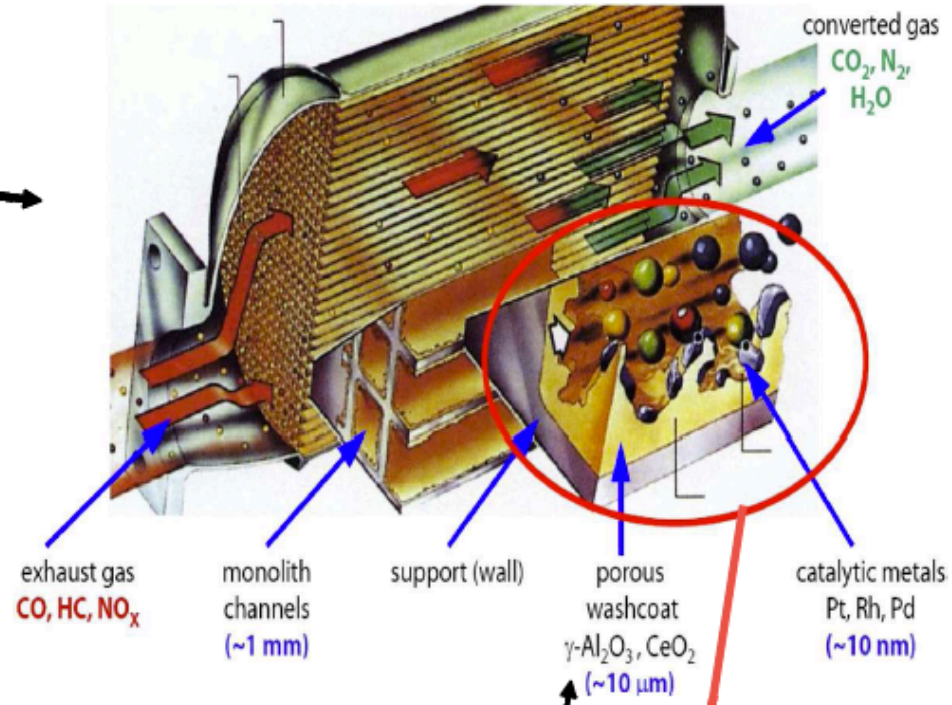
Thermal vs Prompt NOx

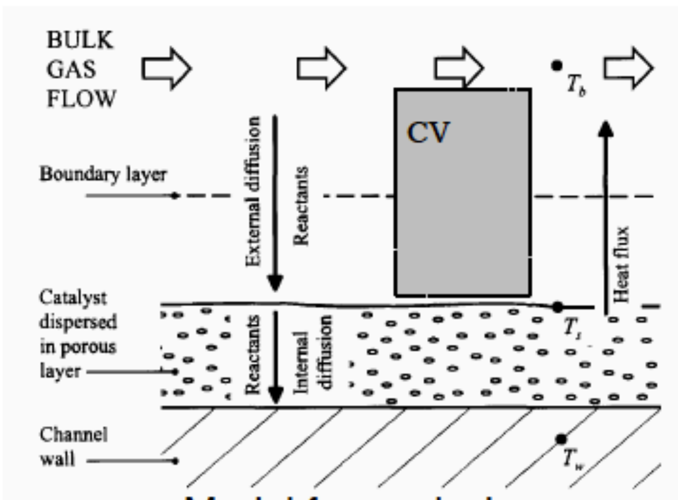


Catalytic Convertor

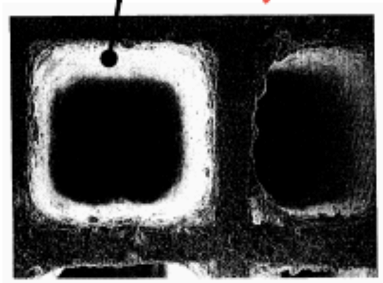


Three-way catalytic monolith reactor (TWC)



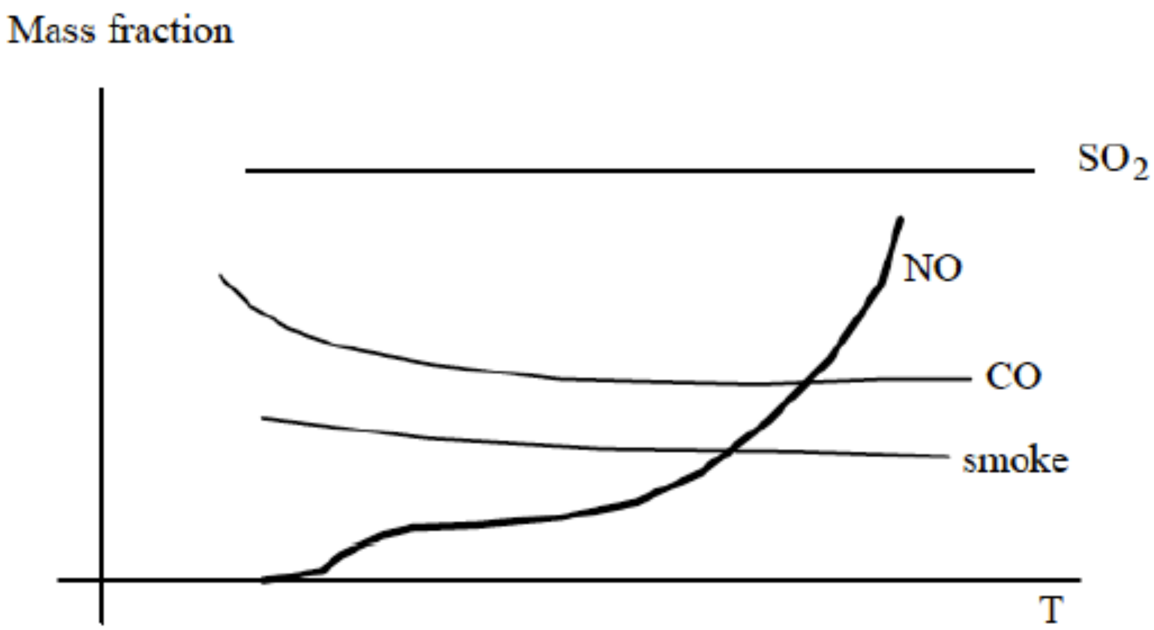


Model for analysis



SEM - image

Summary



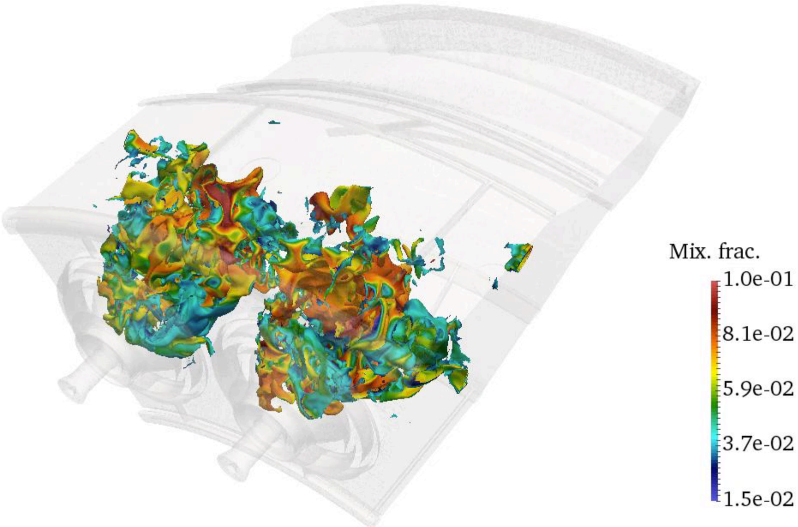
See Table 8-2 for a summary of reduction techniques

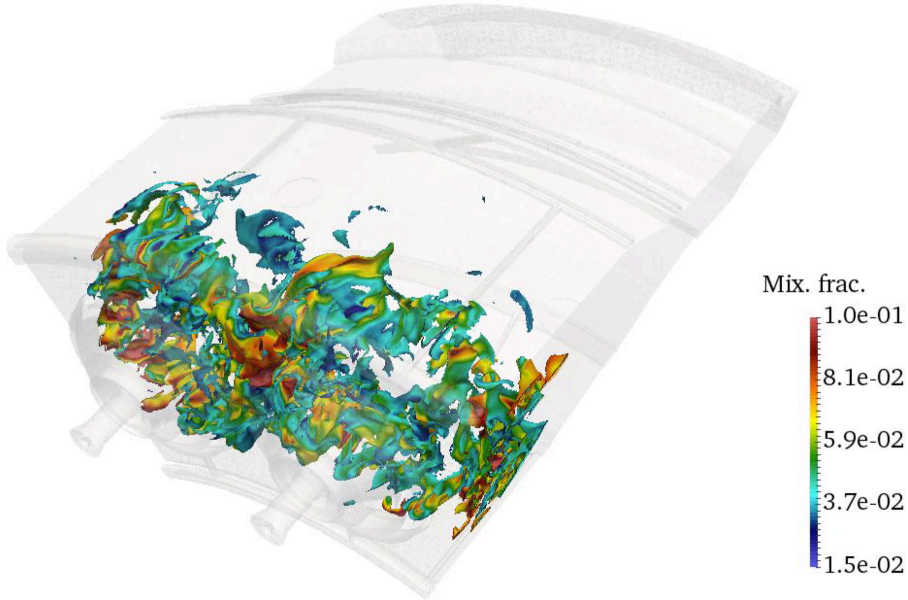
Turbulent Combustion – A Brief Introduction

(not examinable)

Aero – lean burn system

Approach – 16 bar

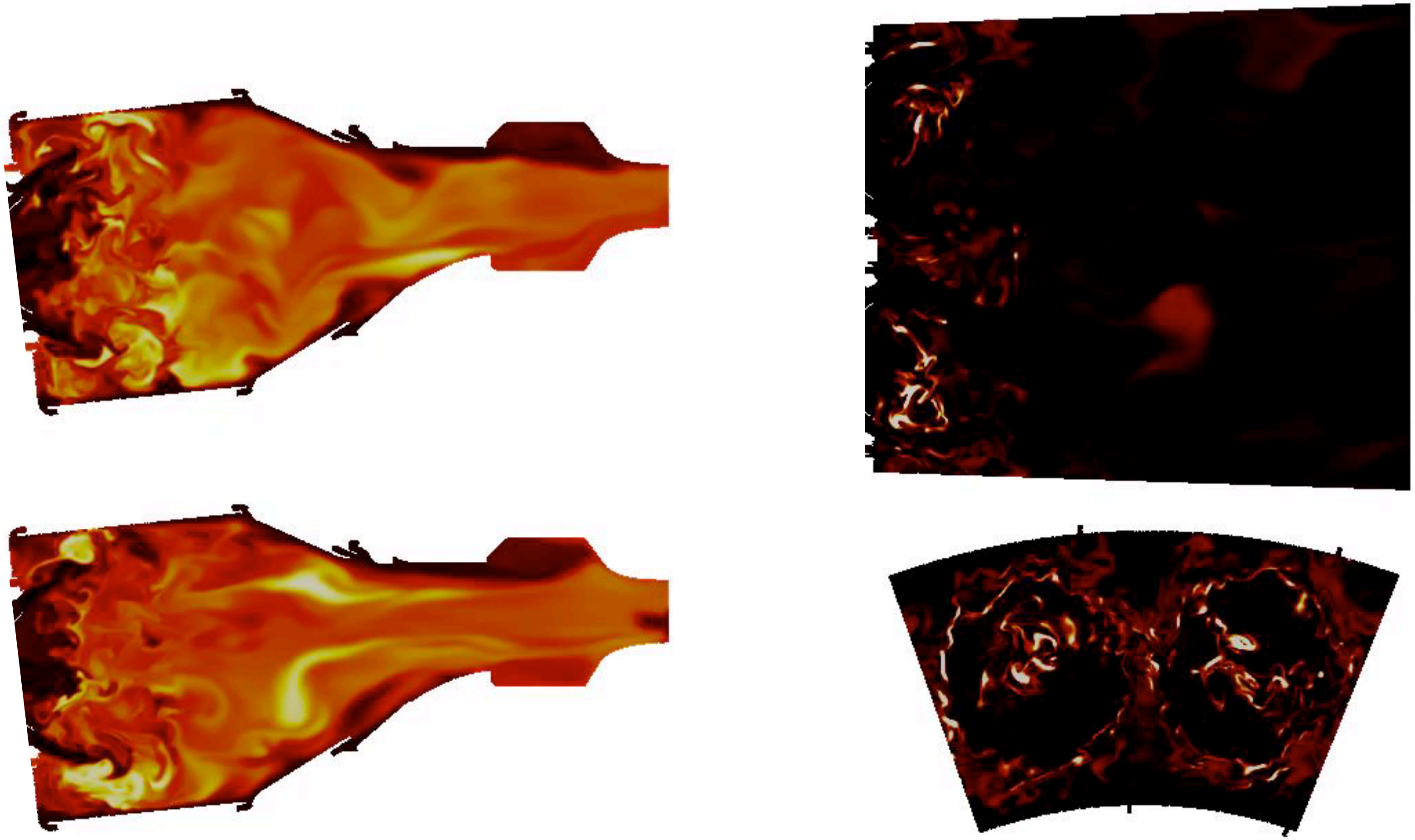




Cutback – 32 bar

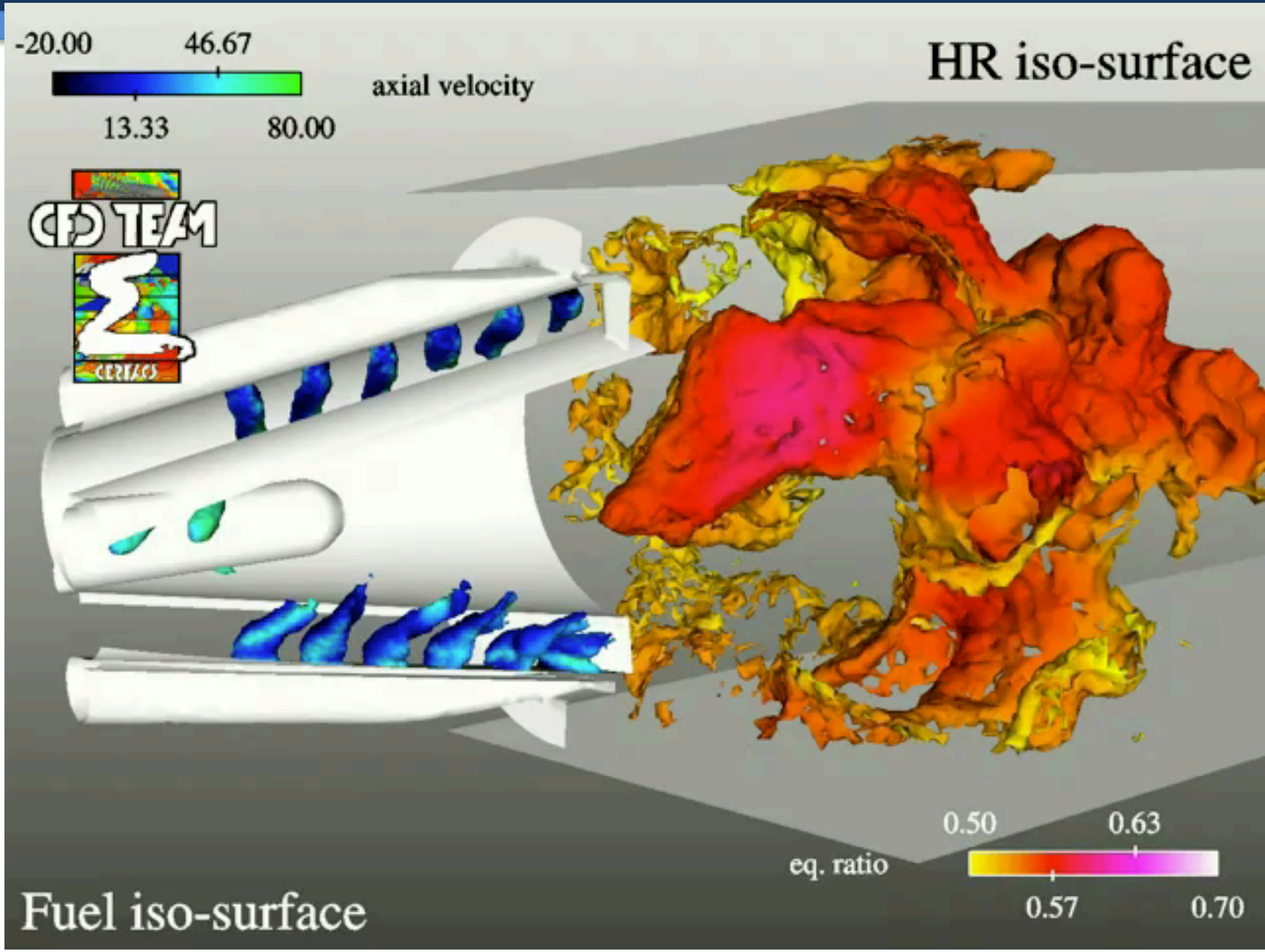
Iso-surface of HRR coloured by mixture fraction

32 bar

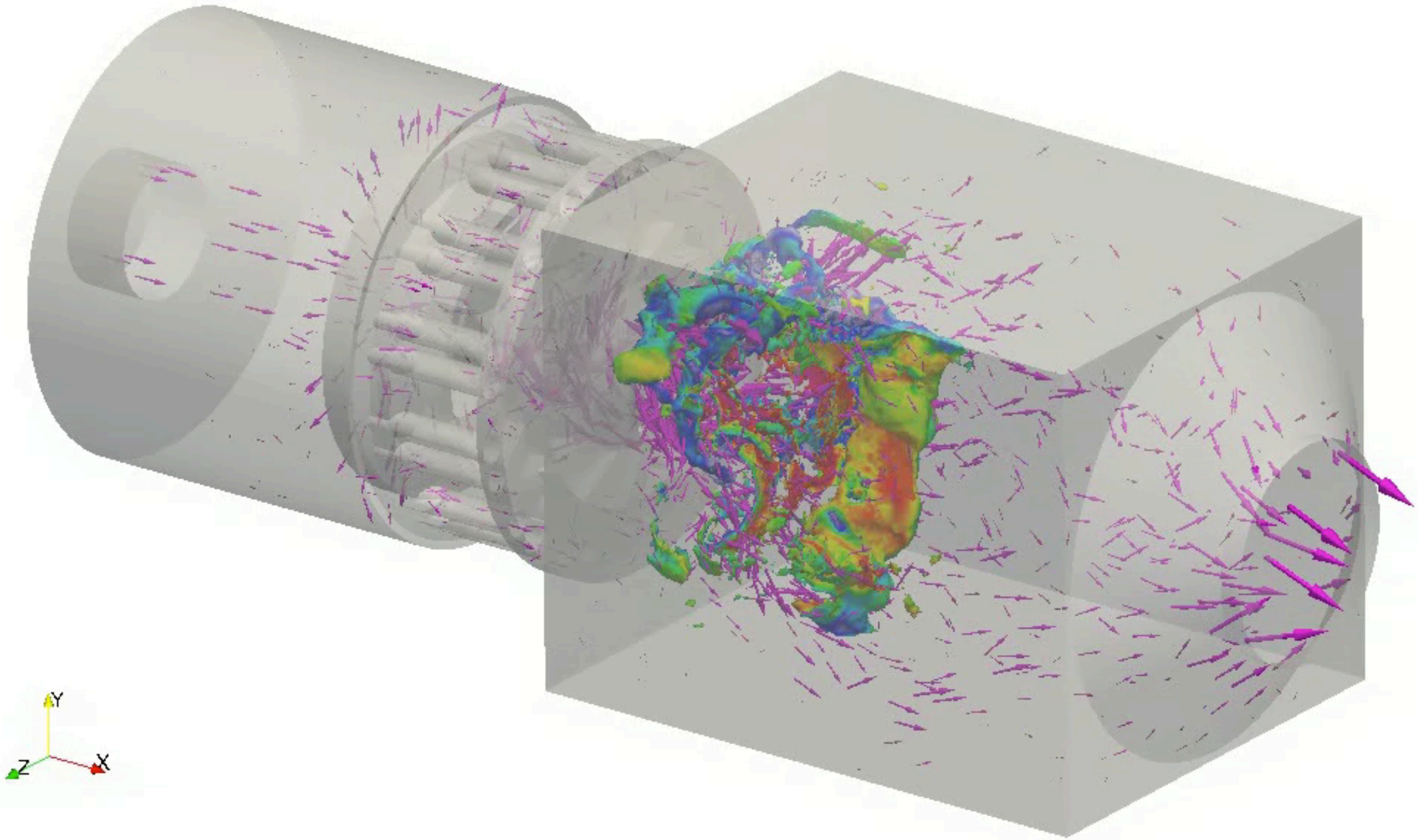


Gas turbine flame simulation

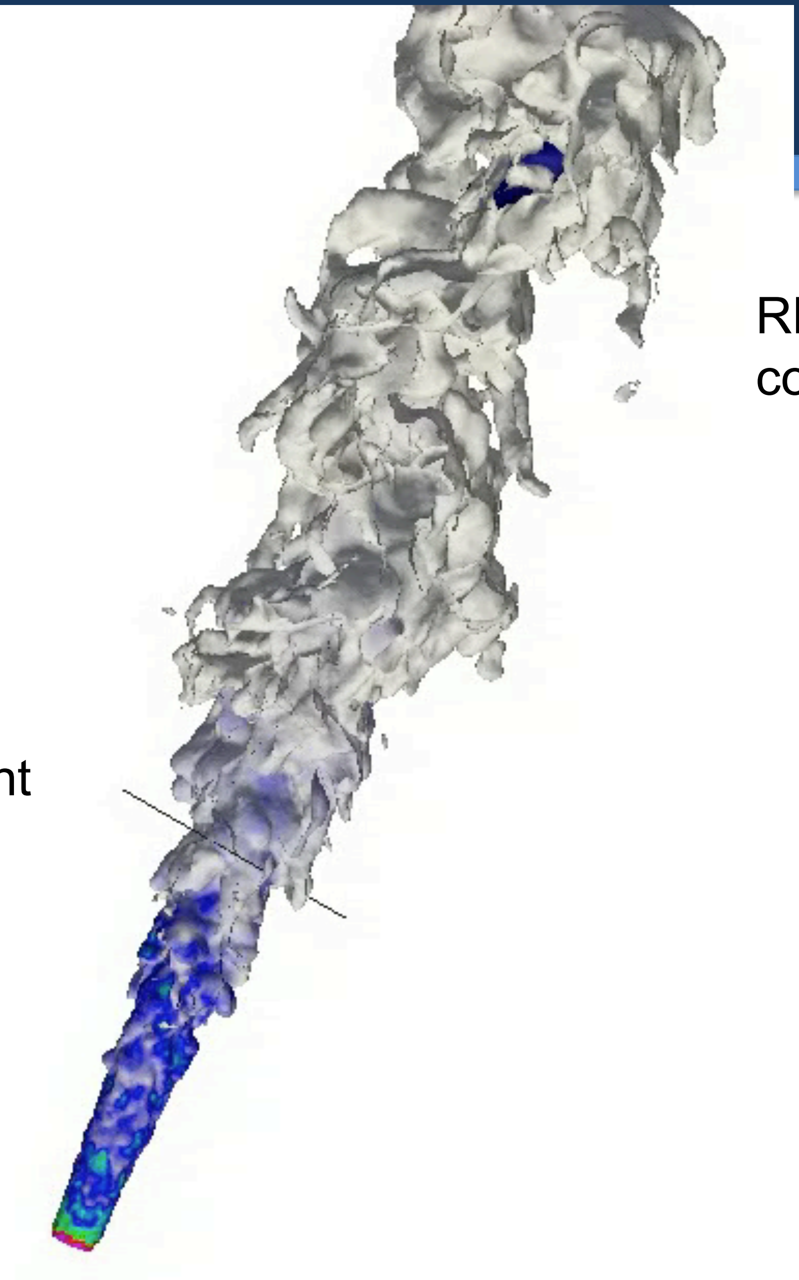
UNIVERSITY OF CAMBRIDGE



Gas turbine flame simulation



Lifted Flame

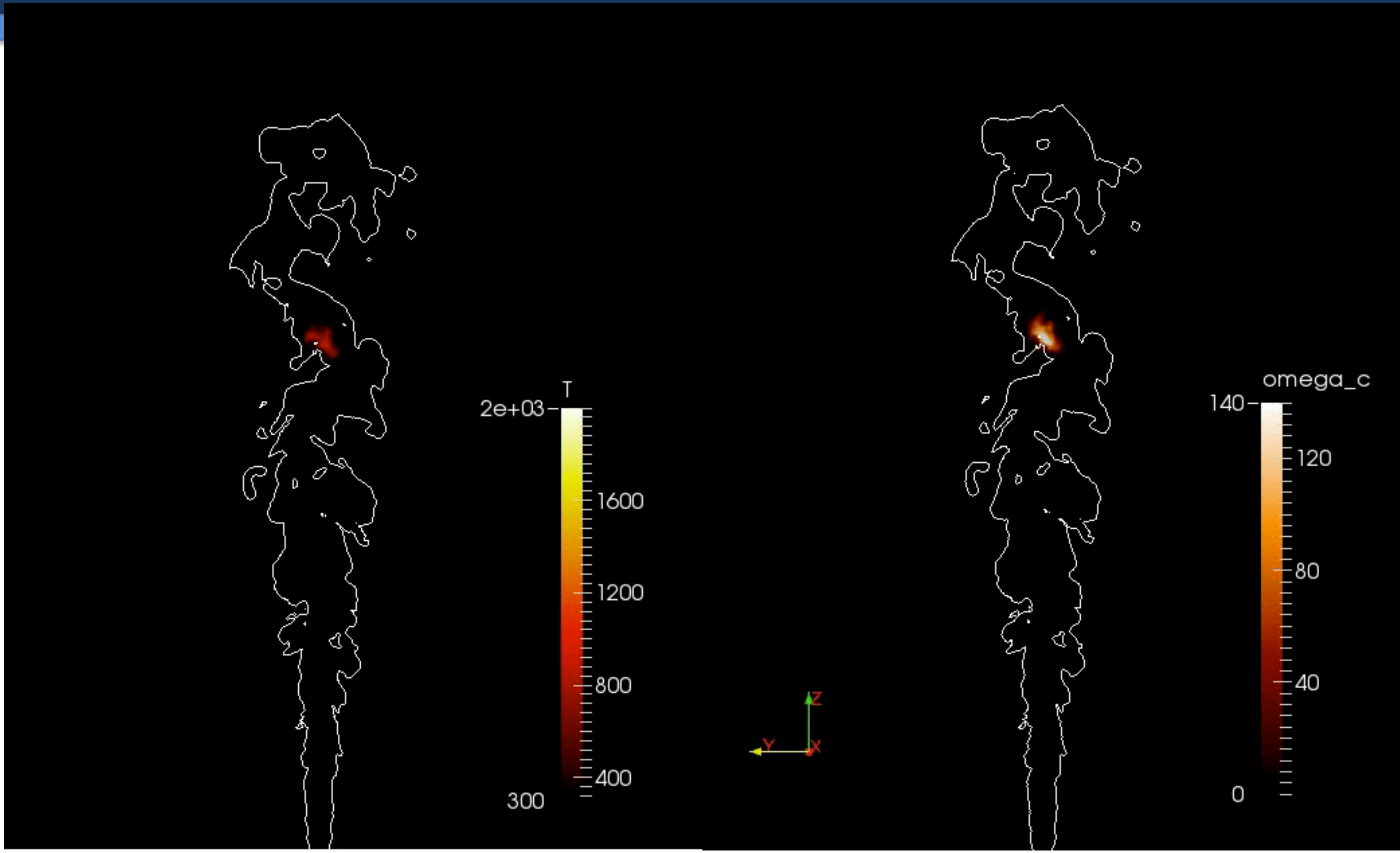


RR iso-surface
coloured by T

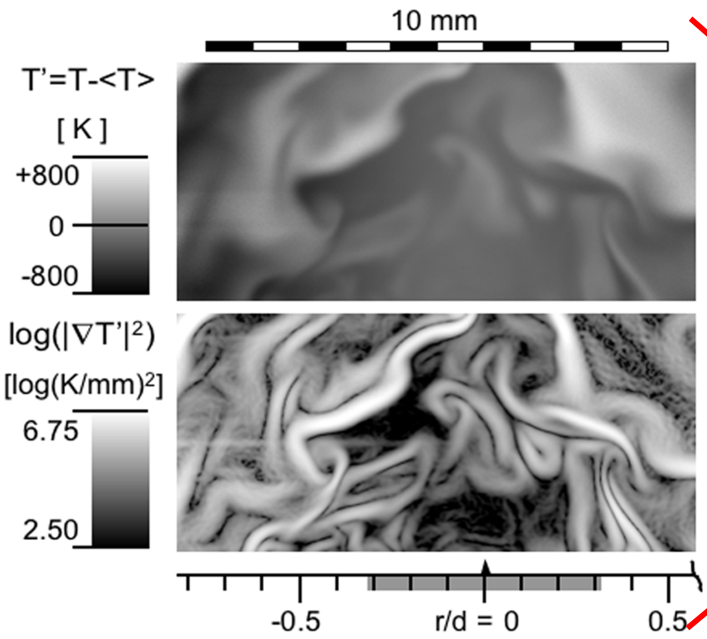
Final flame lift-off height

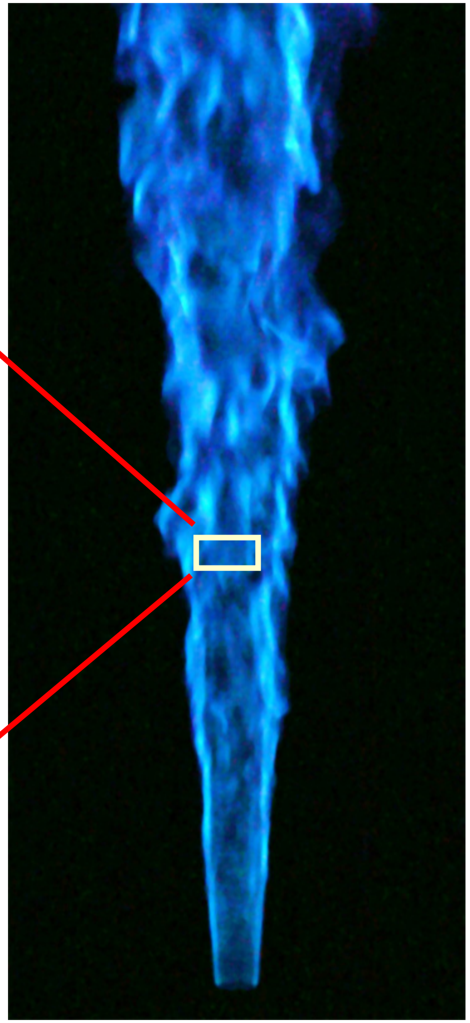
Zst iso-surface
coloured by SDR

2D cut – Lifted flame



A closer view

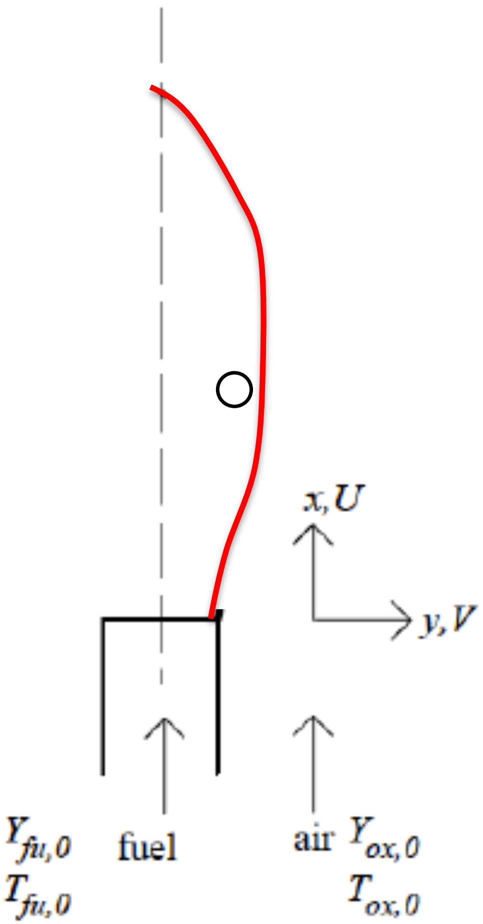


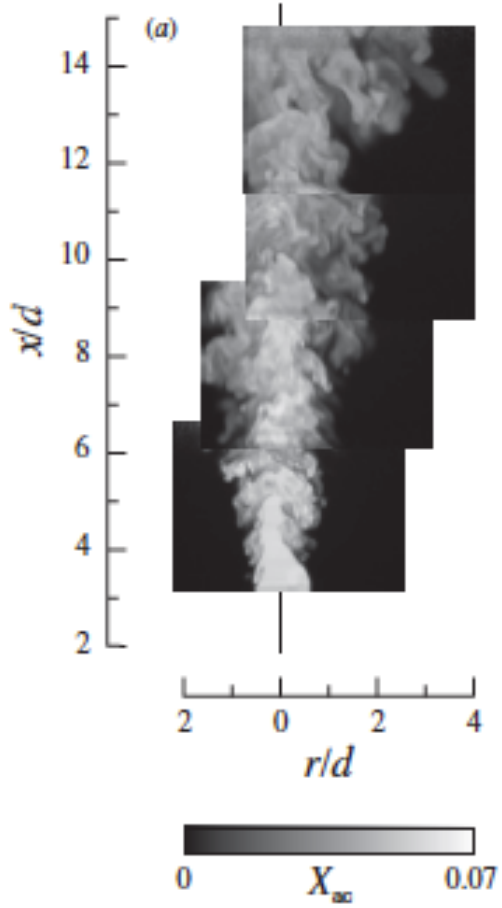


S.A. Kaiser, J.H. Frank,
Proc. Combust. Inst. 31 (2007)

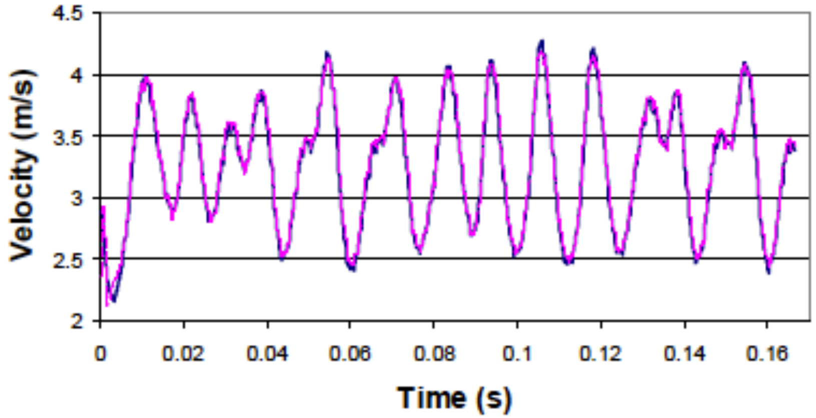
Complex structure
Multi-scales

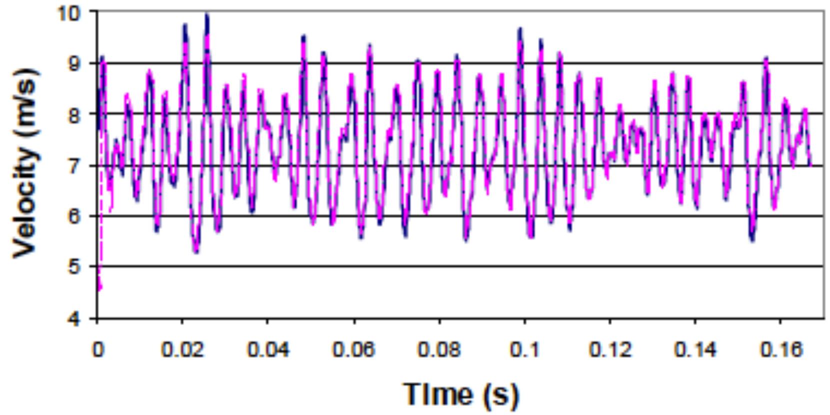
Turbulent Signals





Meas. Sci. Technol. **22** (2011) 085402

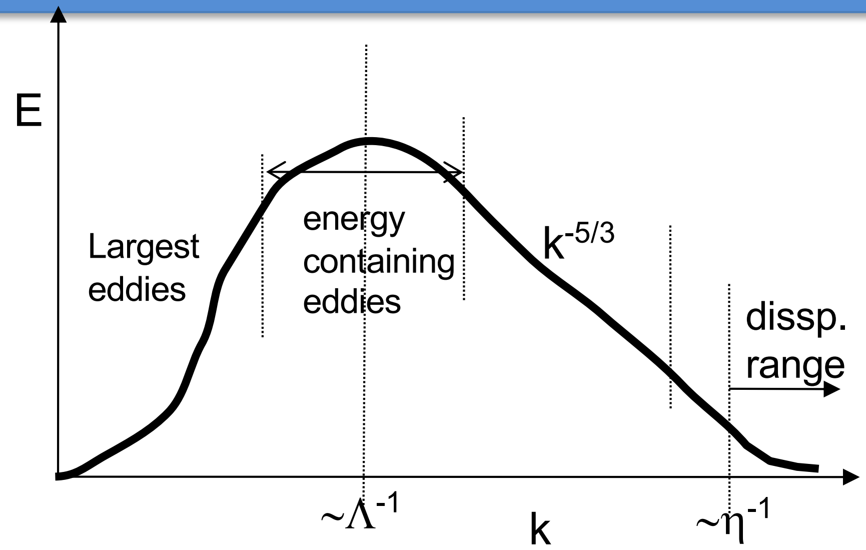




What does this mean? – scales of turbulence

UNIVERSITY OF CAMBRIDGE

- Range of length and time scales
- These scales interact with one another
- Spectrum

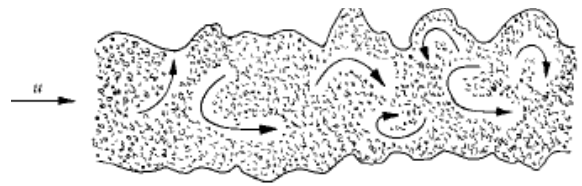


Typical energy containing eddy: integral scale – Λ, τ, u' ; $\tau = \dfrac{\Lambda}{u'}$

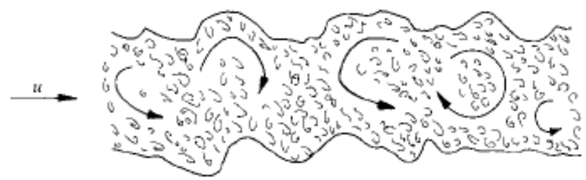
Kolmogorov scales – η, τ_η, u_η

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \qquad \frac{\Lambda}{\eta} = R_t^{3/4}$$

$$\tau_\eta = \left(\frac{\nu}{\epsilon}\right)^{1/2} \qquad \frac{\tau}{\tau_\eta} = R_t^{1/2}$$



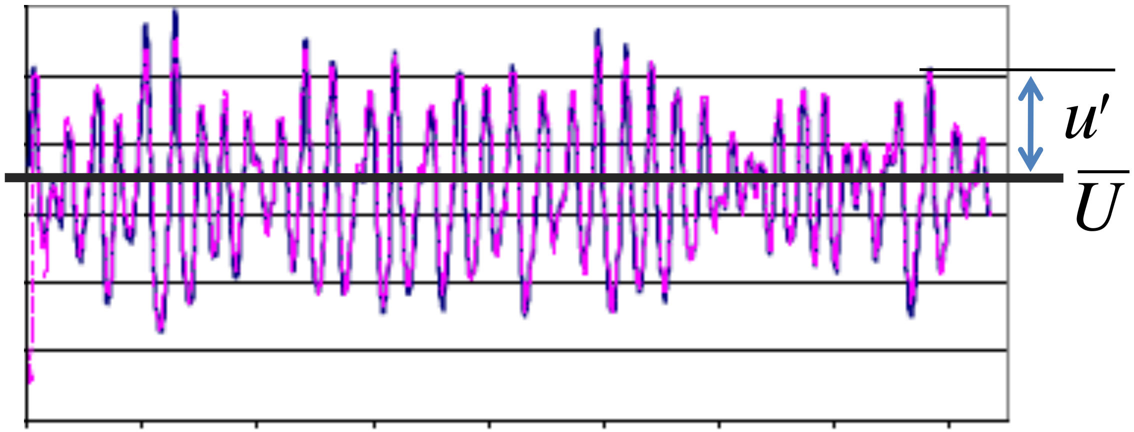
High Re



Modest Re

As R_t increases, small scales decrease
Turbulence becomes finer and finer

Closure Problem - modelling



$$u = \overline{U} + u'$$

In the advective term:

$$\rho uv = \rho\left(\overline{U} + u'\right)\left(\overline{V} + v'\right)$$

$$\rho uT = \overline{\rho}\left(\tilde{U} + u''\right)\left(\tilde{T} + T''\right)$$

density weighted aveg.

When you expand the above expressions

We get terms like $u''v''$ and $u''T''$ - *leading to closure problem (no. of unknowns > no. of Eq.)*

Turbulence modeling comes into play here

Mean values comes from their transport equation

Combustion problem

UNIVERSITY OF CAMBRIDGE

$$\dot{\omega}_1 = \overline{\dot{\omega}}_1 + \dot{\omega}_1' = -A\overline{\rho}^2 \left(\widetilde{Y}_1 + y_1''\right)\left(\widetilde{Y}_2 + y_2''\right)\exp\left(-\frac{T_a}{\widetilde{T} + T''}\right)$$

$$\exp\left(\frac{-T_a}{\widetilde{T}(1+T''/\widetilde{T})}\right) = \exp\left(\frac{-T_a}{\widetilde{T}}\right) \times \left(\sum_{m=0}^{\infty}\frac{(-1)^m}{m!}\left(\frac{T_a}{\widetilde{T}}\right)^m\left[\sum_{n=1}^{\infty}(-1)^n\left(\frac{T''}{\widetilde{T}}\right)^n\right]^m\right)$$

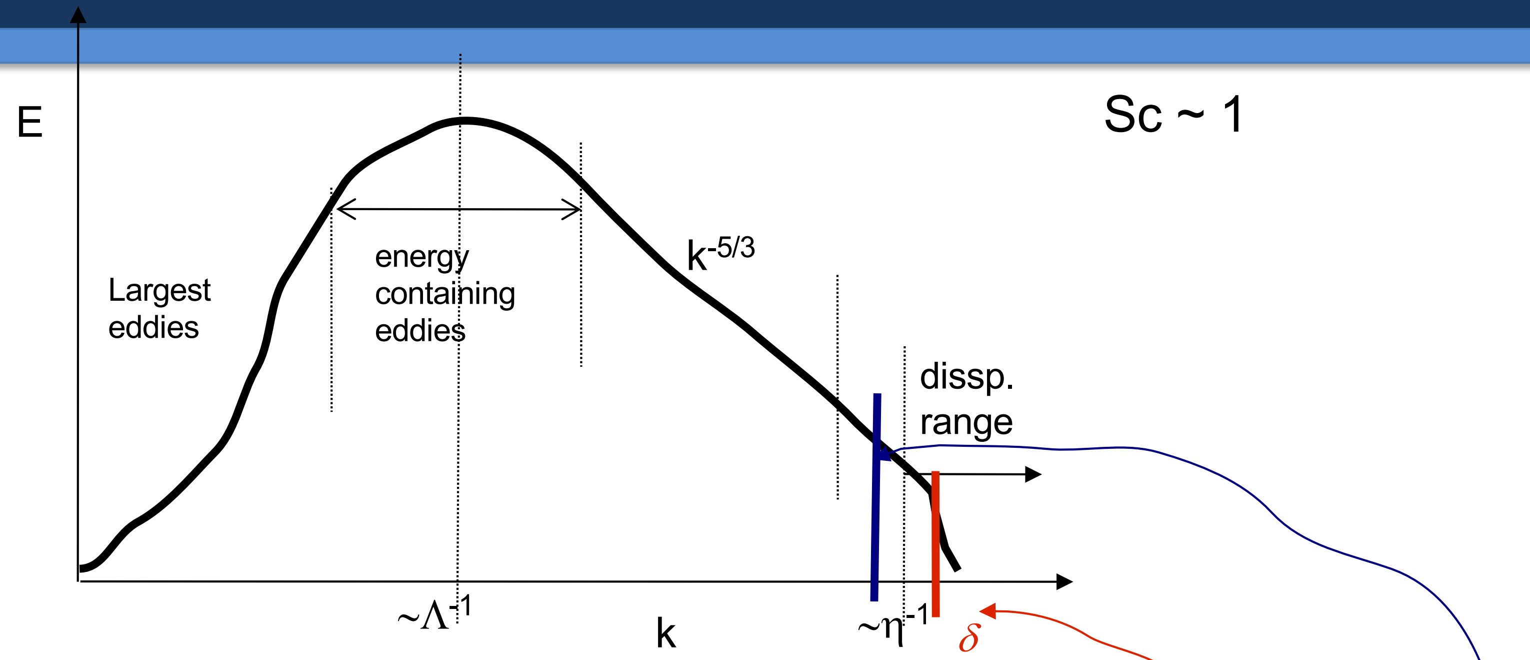
Since $T_a/\widetilde{T}$ is generally large, at least 20 terms are required to have a convergent series

This is not practical – alternative methods “Combustion submodelling” are used

which depends on combustion regime

Combustion Regime

UNIVERSITY OF CAMBRIDGE



- Flamelet combustion: flame scales < Kolmogorov scales
  - turbulent flame is a collection of laminar flames
  - internal structure of laminar flames is undisturbed by the turbulence
- Non-flamelet combustion: flame scales > Kolmogorov scales
  - internal structure of the laminar flame is disturbed by the turbulence

Typical conditions for practical engines

UNIVERSITY OF CAMBRIDGE

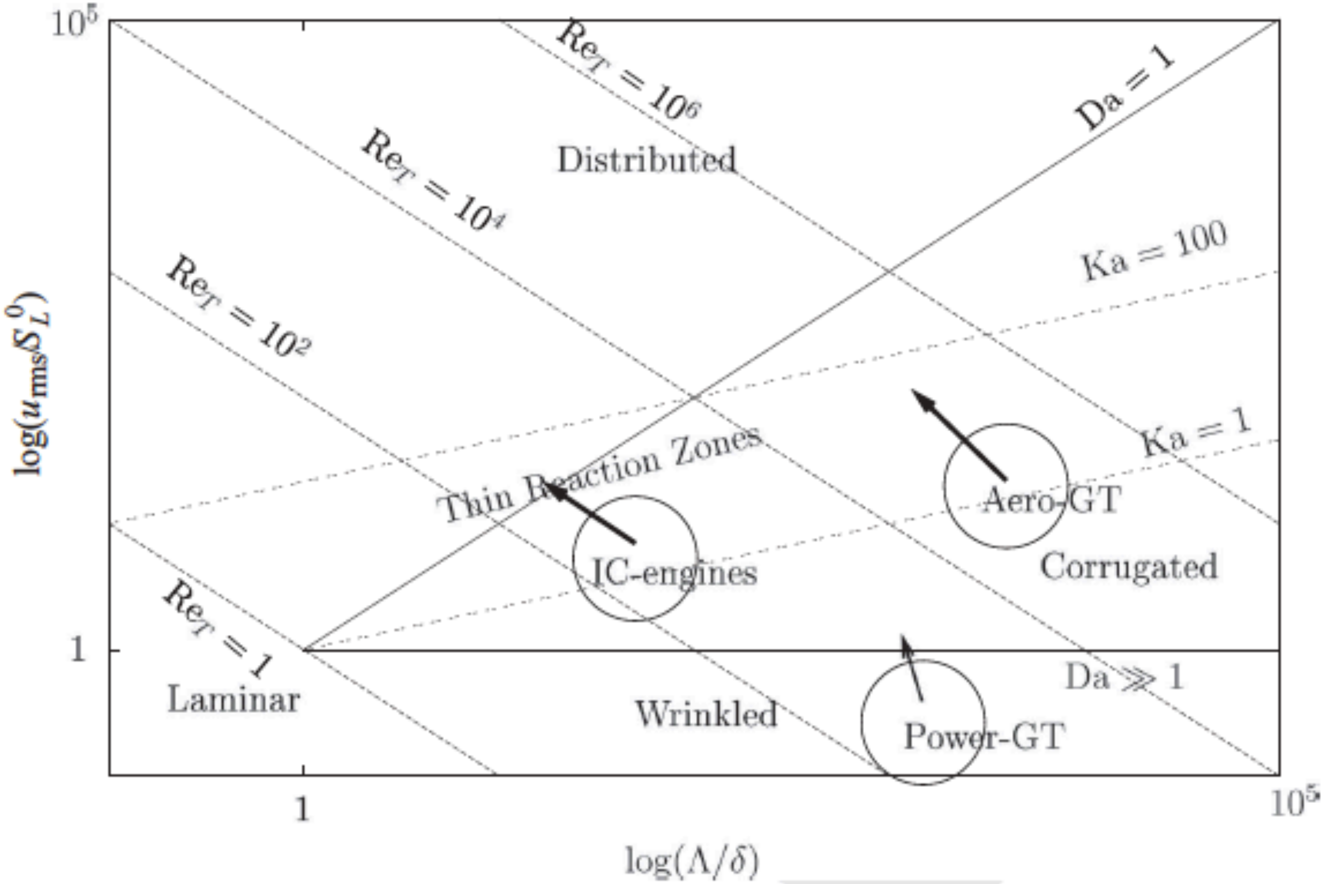


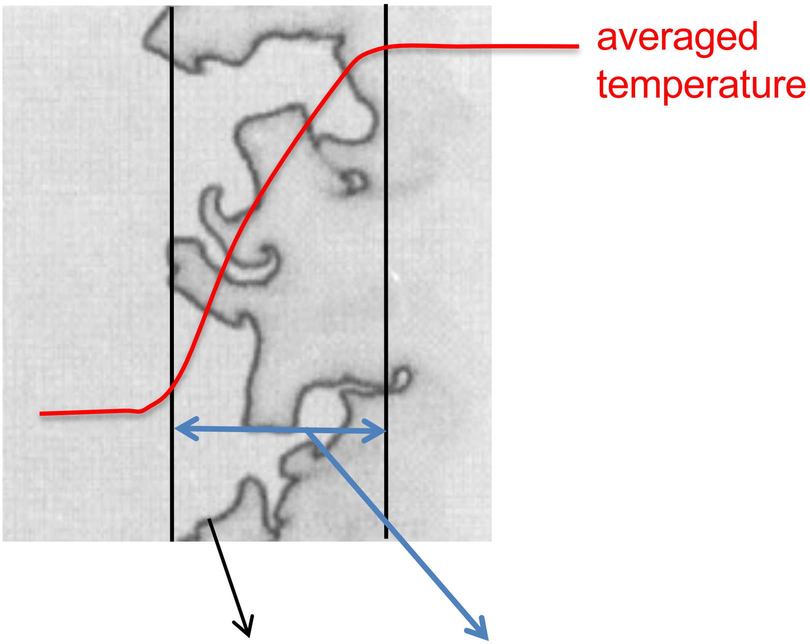
Figure 1.3. Turbulent combustion regime diagram. Typical combustion conditions in three main categories of practical engines are shown, and the arrows indicate the likely direction of change that is due to lean-burn technologies. GT, gas turbine.

Swaminathan & Bray, 2011
"Turbulent Premixed Flames"
Cambridge University Press

Arrows indicate the direction of change for future lean-burn engines

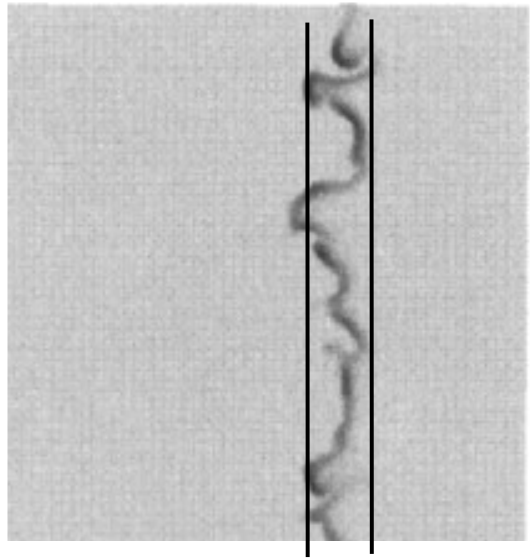
Flame Brush vs Flame Front

low turbulence level



JFM, 281, 1-32, 1994

high turbulence level



Flame Front Vs Flame-brush

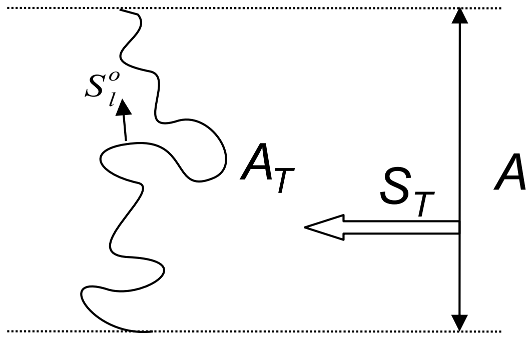
Flame front: instantaneous, corrugate lines in the above pictures

Flame-brush: Averaged, straight lines are the edges of the brush

Effect of turbulence on them

Turbulent Flame Speed

- Turbulent flame speed does not depend on thermochemical properties only
- Depends on attributes of turbulence

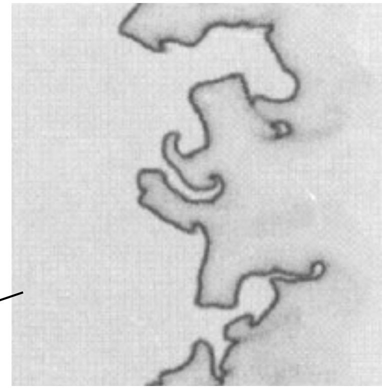


Damkohler hypothesis:
(nearly 70 years ago)

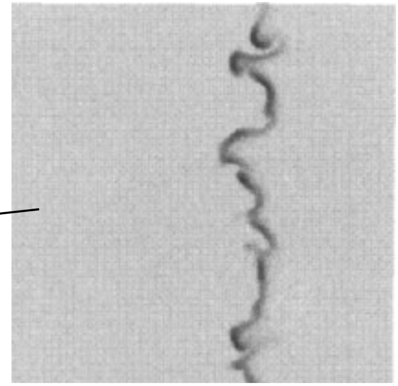
$$\rho_u S_l^o A_T = \rho_u S_T A$$

$$\frac{S_T}{S_l^o} = \frac{A_T}{A} = 1 + \frac{u'}{s_L^o}$$

low turbulence level



high turbulence level



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

$$\frac{S_T}{S_l^o} \simeq \left(\frac{u'\Lambda}{s_L^o\,\delta}\right)^{1/2}$$

S_T is a challenging quantity to predict – recent advances see

Swaminathan & Bray, 2011
"Turbulent Premixed Flames"
Cambridge University Press

Mean Reaction rate – some modelling

UNIVERSITY OF CAMBRIDGE

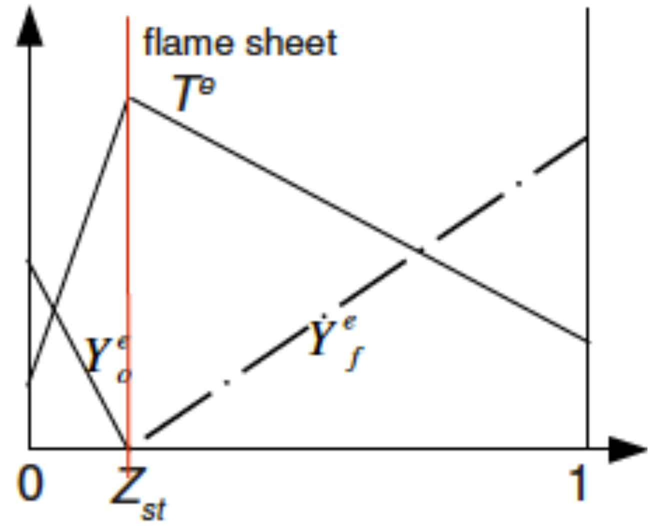
<u>Non-premixed flames:</u>

a number of papers by Spalding in 7th to 14th combust. Symp.
Magnussen & Hjertager, 16th symp. p719
Gran & Magnussen, CST 119, 191-217, 1996
CST 159, 213-235, 2000

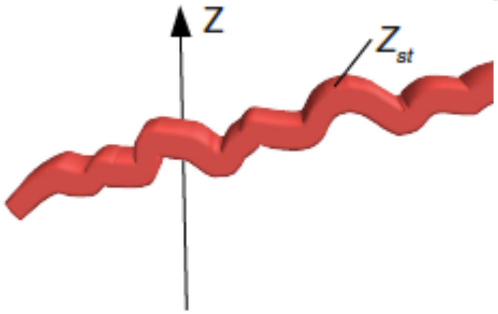
- Eddy break-up models: $\overline{\dot{\omega}_f} = -\overline{\rho}\, C_{ebu} \left(\frac{\tilde{\epsilon}}{\tilde{k}} \right) \widetilde{y_f^2}$

- Mixture fraction based approach

$$\widetilde{Y}_f = \int_0^1 Y_f^e(Z)\, \widetilde{P}(Z)\, dz$$



<u>Flamelet approach</u>



$$\overline{\dot{\omega}} = \int_0^1 \int_0^\infty \dot{\omega}\;\; P(Z, \chi)\, d\chi\, dZ$$

Other approaches
- see the book by Poinsot & Veynante

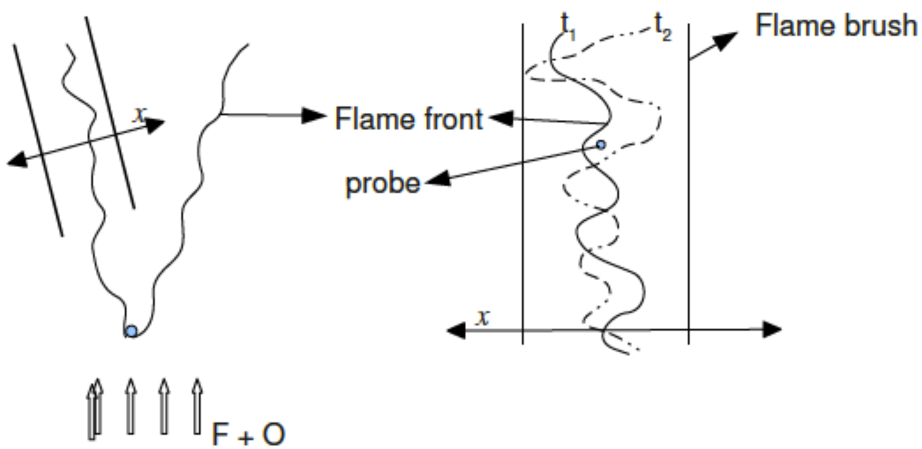
Mean Reaction rate – some modelling

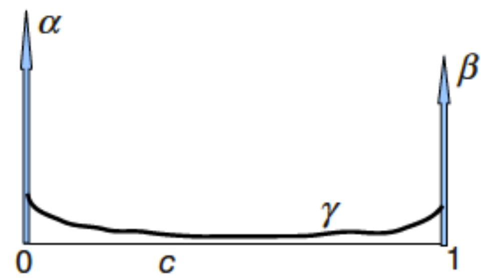
UNIVERSITY OF CAMBRIDGE

Premixed flames:

- Eddy break-up models: $\overline{\dot{\omega}} = \bar{\rho}\, C_{EBU} \left(\frac{\tilde{\epsilon}}{\tilde{k}} \right) \widetilde{c''^2}$

BML approach $\overline{\dot{\omega}} = \frac{2}{(2C_m - 1)} \bar{\rho}\, \tilde{\epsilon}_c$





Other approaches – FSD, G-equ.
- see the book by Poinsot & Veynante

Summary

- Turbulence involves range of length and time scales
- these scales interact with one another - requiring turbulence models
- Combustion introduces additional scales, which interacts with turbulence scales
- Finding closure for turbulence-combustion interaction – challenging task – great amount of research efforts have been spent & continued to be spent
- briefly discussed the turbulent combustion regimes
- briefly discussed simple models
- Despite this topic is common in our life – we know only little about it! => environmental issues via pollution – but our understanding is improving

Next Lect.: Example Class