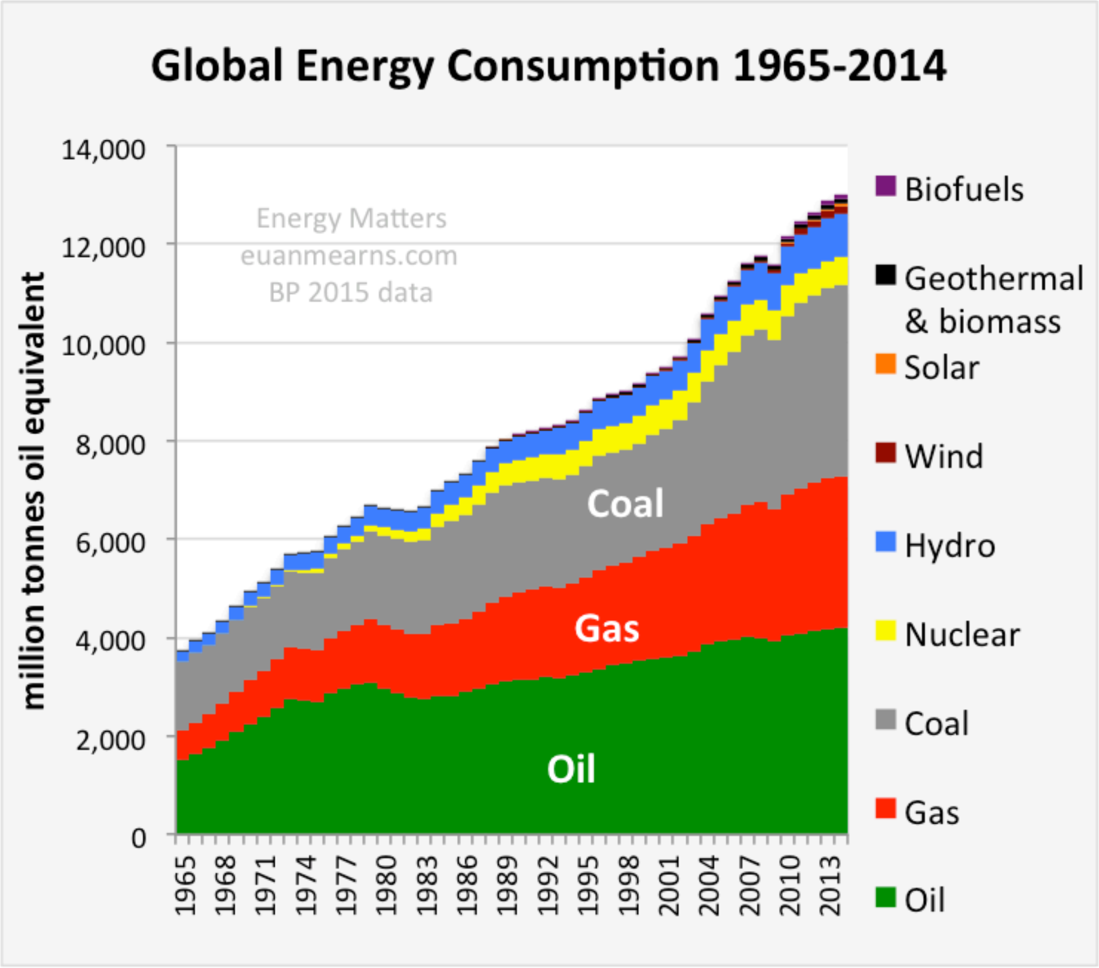
Escoamentos Turbulentos Reativos/ Turbulent Reactive Flows

Aula 1

1.0 Introdução

- Por que estudar combustão Turbulenta?
  - É a mais velha “tecnologia” da humanidade
  - 90% do suprimento de energia mundial ainda é combustão
  - Ocorre em combustíveis fósseis, renováveis ou sintéticos
  - **Problema:** Aquecimento Global e Emissões
  - Novas tecnologias como: oxyfuel, flameless, combustão catalítica e em meios porosos ampliarão o campo de aplicação

1.0 Introduction



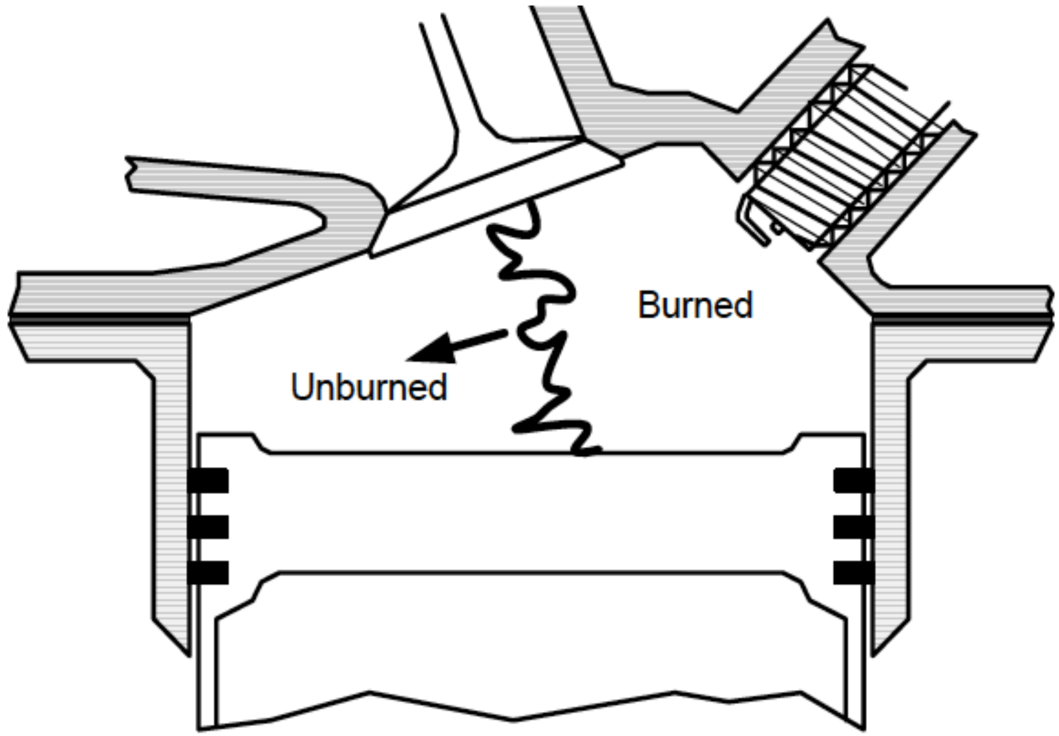
1.0 Introdução

- Chamas básicas
  - Pré-misturada Laminar/Turbulenta
  - Não Pré-misturada – Difusão- Laminar/Turbulenta
  - Parcialmente Pré-Misturadas – Laminar/ Turbulenta

1.0 Introdução

- Chamas Pré-misturada Laminar/Turbulenta
  - Combustível já na forma gasosa e completamente misturado ao oxidante (ar) antes do início do processo de combustão
  - Escoamento Laminar ou Turbulento
  - Exemplos: Motores com Port Fuel Injection e Turbinas a gás com queimadores “Lean-Premixed

1.0 Introdução



- Cross-section of a gasoline engine combustion

1.0 Introdução

- Premixed Flames – Equivalence Ratio Parameter

$$C_3H_8 + 5(O_2 + 3.762N_2) \rightarrow$$
$$4H_2O + 3CO_2 + 18.81N_2$$

- $(A/F)_{stoich}$=air-to-fuel ratio (mass)= (mass of air)/(mass of fuel)
- $(A/F)_{stoich}$=[5(32+3.762*28)]/(44) = 15.6
- $\Phi = (A/F)_{stoich}/(A/F)_{actual}$ = Fuel Equivalence Ratio

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1.0 Introduction

- Premixed Flames – Equivalence Ratio Parameter

  - $\Phi = 1$: stoichiometric combustion
  - $\Phi < 1$: lean mixture, lean combustion
  - $\Phi > 1$: rich mixture, rich combustion

- Premixed Flames – Air ratio is defined as

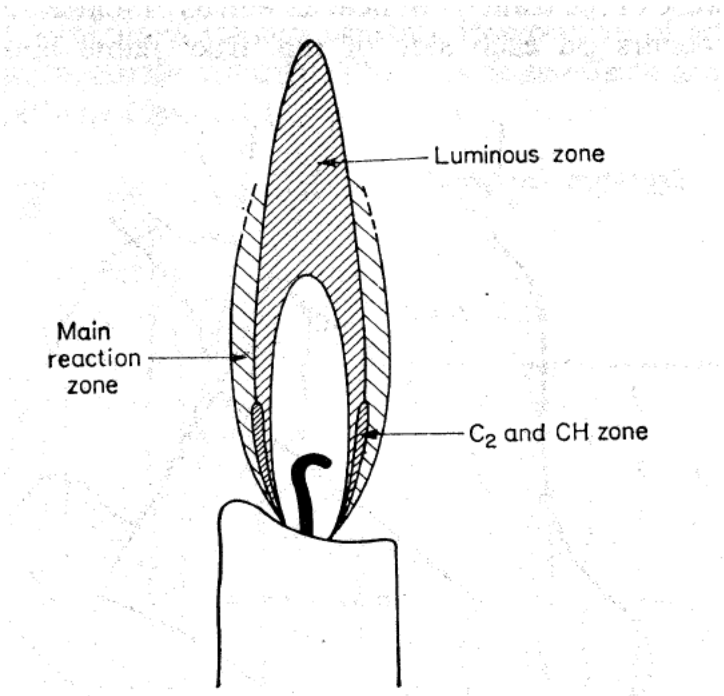
$$\lambda = 1/\Phi$$

1.0 Introduction

- Non Premixed or Diffusion Flames
- Gaseous fuel and air are mixed/come into contact during the combustion process
- Examples:
  - A candle
  - Diesel Engines
  - Conventional aero gas turbines
  - Liquid Bipropellant rocket engines
  - Cement kilns, furnaces
  - Flares in refineries, oil burners
  - Fires
  - Coal and biomass combustors

1.0 Introduction

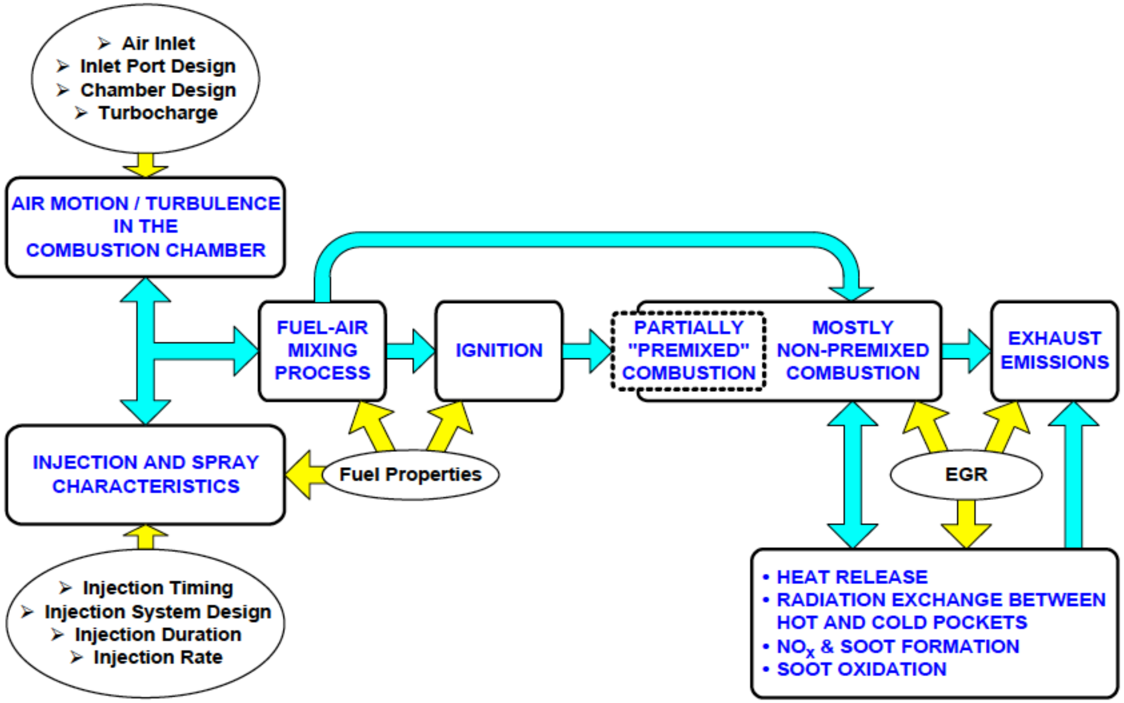
- Non Premixed or Diffusion Flames



A candle flame.

1.0 Introduction

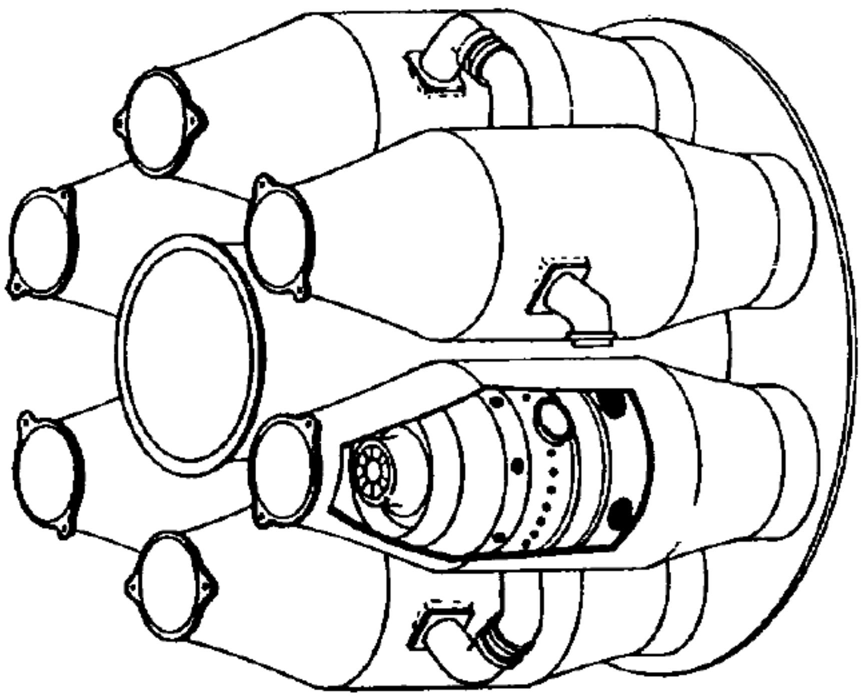
- Non Premixed or Diffusion Flames



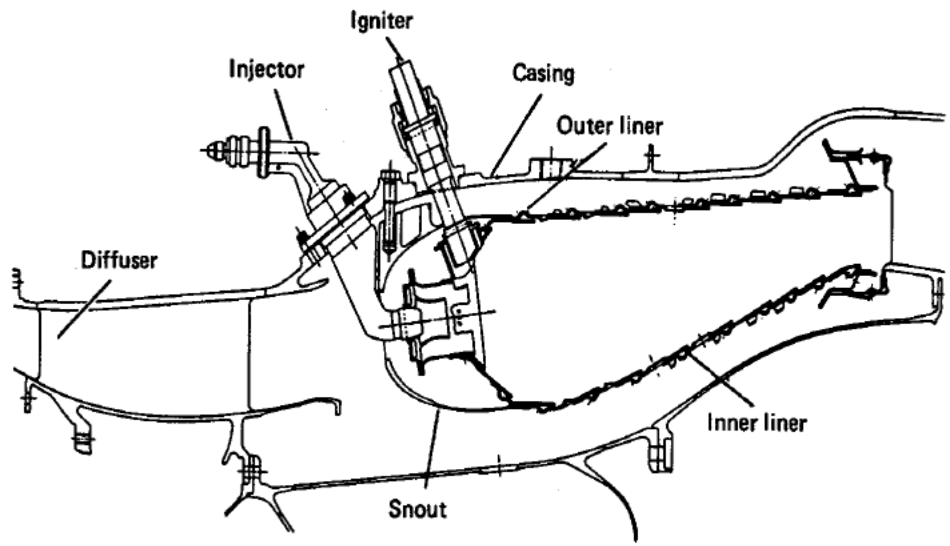
Processes in the diesel engine combustion.

1.0 Introduction

- Non Premixed or Diffusion Flames



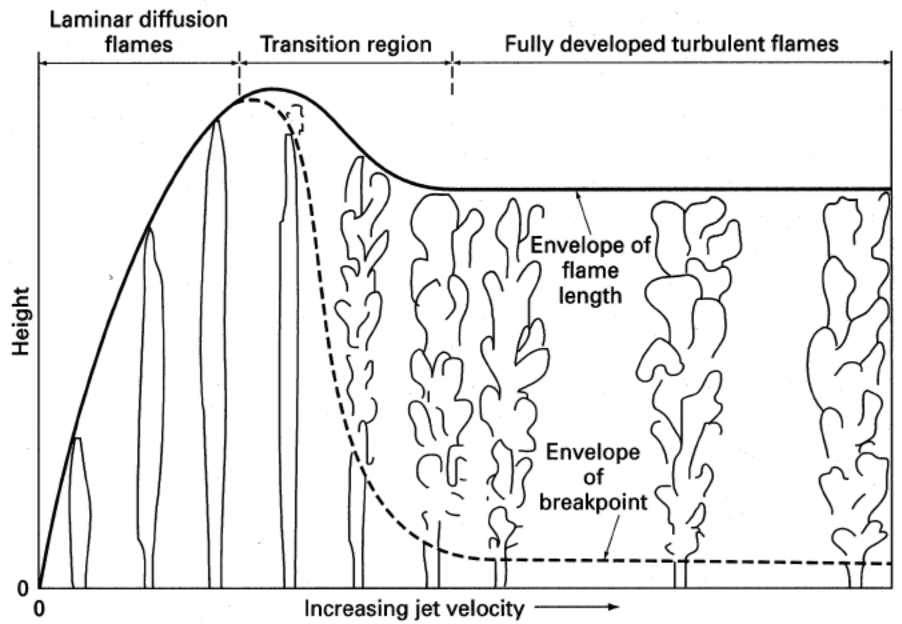
Multi-can combustor arrangement.



Annular Combustor.

1.0 Introduction

- Non Premixed or Diffusion Flames

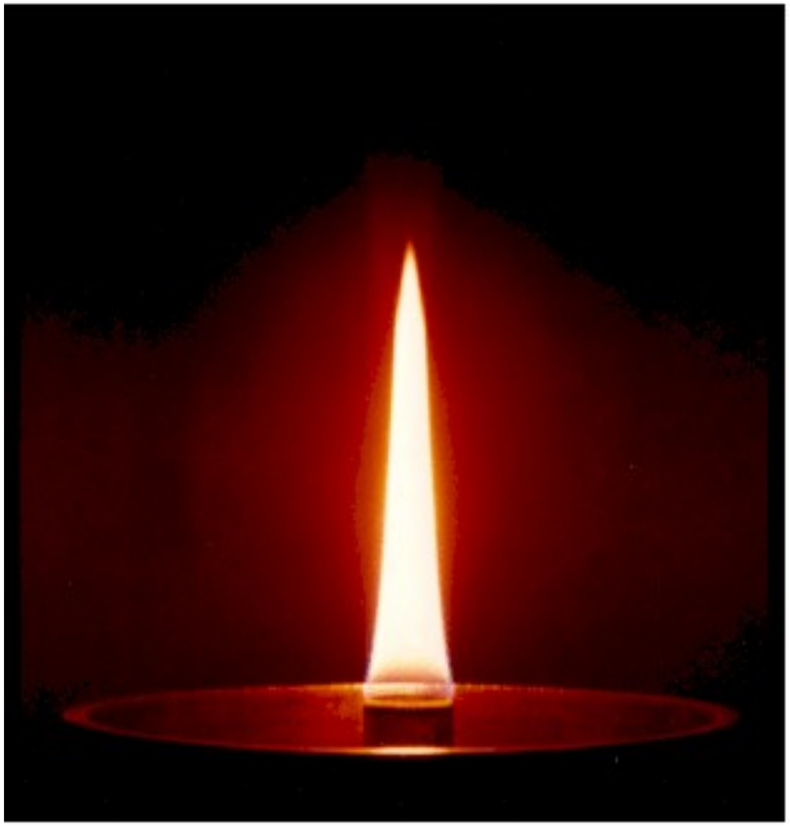


Diffusion Flame Regimes.

1.0 Introduction

- Non Premixed or Diffusion Flames

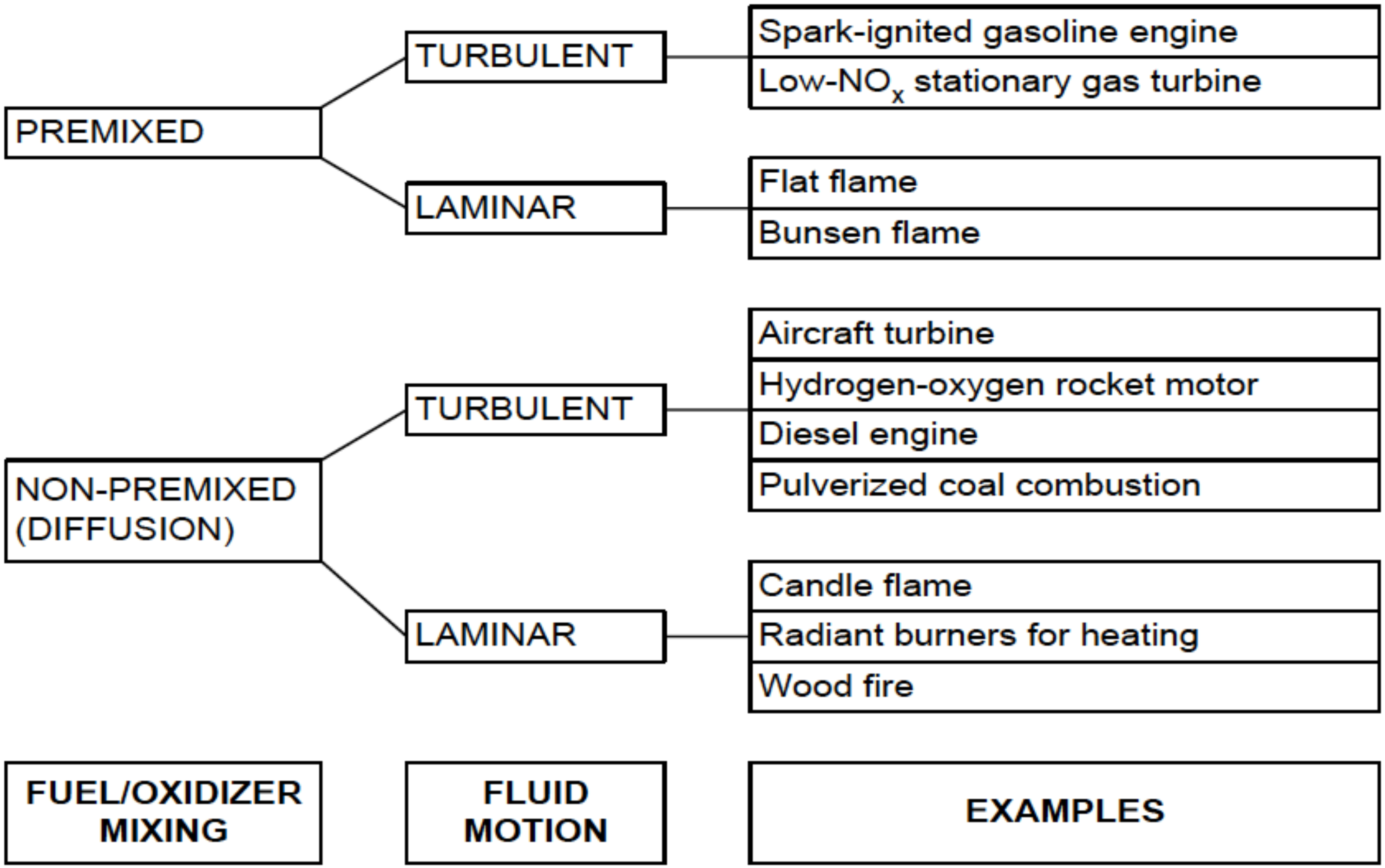
Laminar



C2H4

Turbulent

1.0 Introduction



Examples of combustion systems.

1.0 Introduction

- Some of the issues the combustion designer has to deal with are:
    - Combustion intensity and efficiency
    - Flame stability
    - Flame size and shape
    - Heat Transfer
    - Pollutant formation

2.0 Elementary Descriptions of Turbulence

- Interaction between chemical and flow time scales – Damköhler Number

- Definitions:

- Laminar flame thickness:

$$\delta_L \sim \alpha/S_L = D/S_L = \nu/S_L \qquad (1)$$

- Above equality implies that we assumed,

  Schmidt Number: $\mathrm{Sc} = \nu/D = 1$

  Lewis Number: $\mathrm{Le} = \alpha/D = 1$

  Prandtl Number: $\mathrm{Pr} = \nu/\alpha = 1$

2.0 Elementary Descriptions of Turbulence

- Interaction between chemical and flow time scales – Damköhler Number

  - Turbulent Reynolds number

$$\mathrm{Re}_\Lambda = \frac{u'\Lambda}{\nu} \tag{2}$$

  where Λ is the integral length scale of turbulence.

  - Turbulent Damköhler number: ratio of characteristic flow time, τ_{flow}, to the characteristic chemical time, τ_c.

$$\mathrm{Da} = \frac{\tau_{flow}}{\tau_c} \tag{3}$$

2.0 Elementary Descriptions of Turbulence

- Interaction between chemical and flow time scales – Damköhler Number

  - Characteristic flow time: $\tau_{flow} = \Lambda/u'$
  - Characteristic chemical time: $\tau_c = \delta_L/S_L$
  - Then Damköhler number is:

$$\mathrm{Da} = \frac{S_L \Lambda}{u' \delta_L} \tag{3a}$$

2.0 Elementary Descriptions of Turbulence

- Any property f can be splited into mean and fluctuation as

$$f = \overline{f} + f'$$

- Turbulence strength is generally characterized by the turbulence Intensity

$$I = \sqrt{\overline{f'^2}} \Big/ \overline{f}$$

2.0 Elementary Descriptions of Turbulence

- Turbulence descriptors: lenght and time scales

  1. Integral length scale – related to the characteristic size of the flow l_t
  2. Kolmogorov length scale – the smallest one η

- The Reynolds Number is constructed for each lenght scales

$$\mathrm{Re}_t = \frac{u' l_t}{\nu}$$

100 to 2000 in combustion devices

$$\mathrm{Re}_\eta = \frac{u' \eta}{\nu} \approx 1$$

2.0 Elementary Descriptions of Turbulence

- For homogeneous isotropic turbulence, the energy of the large scales flows to the smaller scales through the Kolmogorov cascade. The energy flux from one scale to another is constant and given by the dissipation rate as

$$\varepsilon = \frac{u'^2(r)}{r/u'(r)} = \frac{u'(r)^3}{r}$$

- At the Kolmogorov scales, from the unity Re, one has

$$\mathrm{Re}_\eta = \frac{u_k'\eta}{\nu} = 1 = \frac{u_k'\ \eta}{\nu} = \frac{\varepsilon^{1/3}\eta^{1/3}\eta}{\nu} = \frac{\varepsilon^{1/3}\eta^{4/3}}{\nu}$$

2.0 Elementary Descriptions of Turbulence

- The Kolmogorov length scales reads then

$$\eta = \left(\nu^3 / \varepsilon\right)^{1/4}$$

- The ratio of the integral to the Kolmogorov length scales is

$$\frac{l_t}{\eta} = \frac{u'^3 / \varepsilon}{\left(\nu^3 / \varepsilon\right)^{1/4}} = \mathrm{Re}_t^{3/4}$$

2.0 Elementary Descriptions of Turbulence

- The Integral length scales can be evaluated from the correlation coefficient as

$$R_x(r) = \frac{\overline{u'_x(0)u'_x(r)}}{u'_{x,rms}(0)u'_{x,rms}(r)}$$

Integrated over a distance between two points

$$l_t = \int_0^\infty R_x(r)\,dr$$

2.0 Elementary Descriptions of Turbulence

- For statistically stationary process (what does it mean ?)
- The Integral time scales can be evaluated from the auto-correlation as

$$R_x(\tau) = \overline{u'_x(0)u'_x(\tau)}$$

The normalized autocorrelation coefficient is

$$\rho(\tau) = \frac{R_x(\tau)}{\overline{u'^2_x}}$$

2.0 Elementary Descriptions of Turbulence

The Integral time scale can be evaluated from the integration over the time interval

$$\tau_t = \int_0^\infty \rho(\tau)\,d\tau$$

The Integral time scale gives the rough measure of the interval over which u(t) is correlated with itself.

2.0 Elementary Descriptions of Turbulence

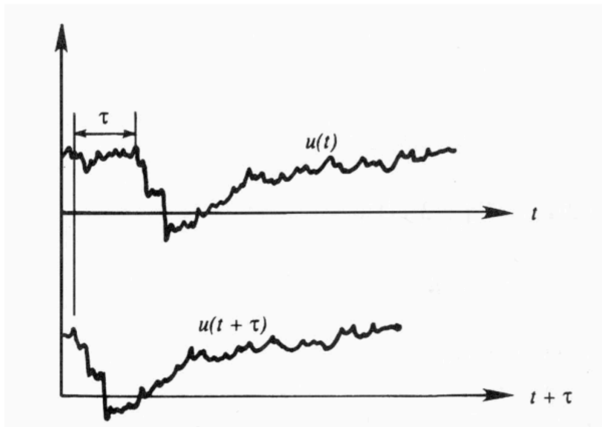


Figure 4.1: Method of calculating the autocorrelation $R(\tau) = \langle u(t)u(t+\tau)\rangle$. This figure has been taken from *Kundu and Cohen* [2002].

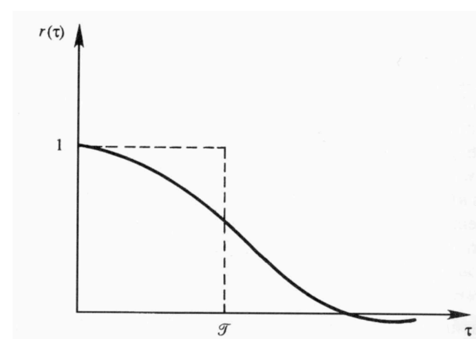


Figure 4.2: Autocorrelation function $r(\tau)$ and the integral time scale $\mathcal{T}$. This figure has been taken from *Kundu and Cohen* [2002].